AD-A088 104 ROCKWELL INTERNATIONAL NEWBURY PARK CA ENVIRONMENTAL--ETC F/G 11/1
FOAM PLUG DEVELOPMENT.(U)
DEC 79 R W MELVOLD, W TU, G H SMITH DOT-CG-81-78-1817
UNCLASSIFIED EMSC8316.1FR USCG-D-30-80 NL

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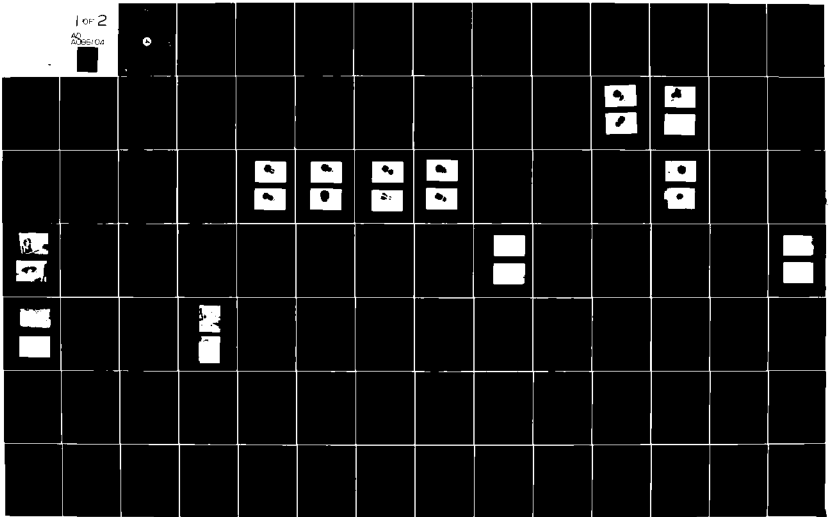

REPORT NO: CG-D-30-80

LEVEL II

(12) B.S.

# FOAM PLUG DEVELOPMENT


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Avery Point Groton, Connecticut 06340



DECEMBER 1979

FINAL REPORT


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PREPARED FOR

U. S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON D. C. 20593

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**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No.<br>CG-D-30-80 | 2. Government Accession No.<br>AD-A088104 | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>Foam Plug Development 11 | | 5. Report Date<br>Dec[redacted]79 |
| 14 | | 6. Performing Organization Code |
| | | 8. Performing Organization Report No. |
| 7. Author(s)<br>Robert W. Melvold, Wen-Hsiung Tu, George H. Smith | | EMSC8316.1FR |
| 9. Performing Organization Name and Address<br>Rockwell International<br>Environmental Monitoring & Services Center<br>2421 West Hillcrest Drive<br>Newbury Park, CA 91320 | | 10. Work Unit No. (TRAIS)<br><br>11. Contract or Grant No.<br>DOT-CG-81-78-1817 (Mod. 8) |
| 12. Sponsoring Agency Name and Address<br>Department of Transportation<br>United States Coast Guard<br>Research & Development Center<br>Groton, CT 06340 | | 13. Type of Report and Period Covered<br>Final Report<br>Janu[redacted] — Dec[redacted]79<br><br>14. Sponsoring Agency Code<br>R&DC 1/80 |

15. Supplementary Notes

Appendix E contains handout sheets for the external leak plugger training program.

16. Abstract

The program was conducted to improve an existing leak-plugging system, designed for plugging underwater holes up to 0.1 meter (4 inches) in diameter, and to modify it to satisfy the requirements for use by Coast Guard pollution response personnel. Eight prototypes of the external leak plugger were fabricated and extensively tested, both in the laboratory and in the field, the latter by Coast Guard Strike Team divers. The reliability of the device was verified. It was used to adequately plug holes well beyond the design limits and within seconds of activation by an operator. Aspects of satisfactory plug formation were thoroughly investigated, resulting in dramatic improvements in the applicator tip design. A large-scale loading system for formulating significant quantities of polystyrene foam and for loading individual devices with the premixed foam was developed and used. A large plug feasibility study showed no insurmountable engineering problems precluding the development and use of a scaled-up leak-plugging system. A detailed analytical investigation of sizing requirements, loading requirements, and environmental considerations produced a recommended system configuration with a high probability for system success. A system integration study furthered the production and deployment of the external leak plugger by selecting the optimum leak plugger shipping configuration, determining the most cost-effective approach for producing the external leak plugger in quantity, filing a formal application with the DOT for exempting the loaded device from certain shipping regulations, and preparing a training program, including a narrated color film and a slide presentation, to train the Strike Team divers in the proper use and operation of the external leak plugger.

| | |
|---|---|
| 17. Key Words<br>Applicator Tip, Hazardous Materials, External Leak Plugger, Hull Rupture, Foam Lance, Leak Prevention, Foam Plug, Polystyrene Foam, Strike Team Divers | 18. Distribution Statement<br>Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia, 22161 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 144 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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# Conversion Factors as Exact Numerical Multiples of SI Units

**The first two digits of each numerical entry represent a power of 10. For example, the entry "—02 2.54" expresses the fact that 1 inch = 2.54 × 10⁻² meter.**

## Metric Conversion Factors

| *To convert from* | *to* | *multiply by* |
|---|---|---|
| abampere | ampere | +01 1.00 |
| abcoulomb | coulomb | +01 1.00 |
| abfarad | farad | +09 1.00 |
| abhenry | henry | −09 1.00 |
| abmho | mho | +09 1.00 |
| abohm | ohm | −09 1.00 |
| abvolt | volt | −08 1.00 |
| acre | meter$^2$ | +03 4.046 856 |
| ampere (international of 1948) | ampere | −01 9.998 35 |
| angstrom | meter | −10 1.00 |
| are | meter$^2$ | +02 1.00 |
| astronomical unit | meter | +11 1.495 978 |
| atmosphere | newton/meter$^2$ | +05 1.013 25 |
| bar | newton/meter$^2$ | +05 1.00 |
| barn | meter$^2$ | −28 1.00 |
| barrel (petroleum, 42 gallons) | meter$^3$ | −01 1.589 873 |
| barye | newton/meter$^2$ | −01 1.00 |
| British thermal unit (ISO/TC 12) | joule | +03 1.055 06 |
| British thermal unit (International Steam Table) | joule | +03 1.055 04 |
| British thermal unit (mean) | joule | +03 1.055 87 |
| British thermal unit (thermochemical) | joule | +03 1.054 350 |
| British thermal unit (39° F) | joule | +03 1.059 67 |
| British thermal unit (60° F) | joule | +03 1.054 68 |
| bushel (U.S.) | meter$^3$ | −02 3.523 907 |
| cable | meter | +02 2.194 56 |
| caliber | meter | −04 2.54 |
| calorie (International Steam Table) | joule | +00 4.1868 |
| calorie (mean) | joule | +00 4.190 02 |
| calorie (thermochemical) | joule | +00 4.184 |
| calorie (15° C) | joule | +00 4.185 80 |
| calorie (20° C) | joule | +00 4.181 90 |
| calorie (kilogram, International Steam Table) | joule | +03 4.186 8 |
| calorie (kilogram, mean) | joule | +03 4.190 02 |
| calorie (kilogram, thermochemical) | joule | +03 4.184 |
| carat (metric) | kilogram | −04 2.00 |
| Celsius (temperature) | kelvin | $t_K = t_C + 273.15$ |
| centimeter of mercury (0° C) | newton/meter$^2$ | +03 1.333 22 |
| centimeter of water (4° C) | newton/meter$^2$ | +01 9.806 38 |
| chain (engineer or ramden) | meter | +01 3.048 |
| chain (surveyor or gunter) | meter | +01 2.011 68 |
| circular mil | meter$^2$ | −10 5.067 074 |
| cord | meter$^3$ | +00 3.624 556 |
| coulomb (international of 1948) | coulomb | −01 9.998 35 |
| cubit | meter | −01 4.572 |
| cup | meter$^3$ | −04 2.365 882 |
| curie | disintegration/second | +10 3.70 |
| day (mean solar) | second (mean solar) | +04 8.64 |
| day (sidereal) | second (mean solar) | +04 8.616 409 |
| degree (angle) | radian | −02 1.745 329 |
| denier (international) | kilogram/meter | −07 1.00 |
| dram (avoirdupois) | kilogram | −03 1.771 845 |
| dram (troy or apothecary) | kilogram | −03 3.887 934 |
| dram (U.S. fluid) | meter$^3$ | −06 3.696 691 |
| dyne | newton | −05 1.00 |
| electron volt | joule | −19 1.602 10 |
| erg | joule | −07 1.00 |
| Fahrenheit (temperature) | kelvin | $t_K = (5/9)(t_F + 459.67)$ |
| Fahrenheit (temperature) | Celsius | $t_C = (5/9)(t_F - 32)$ |
| farad (international of 1948) | farad | −01 9.995 05 |
| faraday (based on carbon 12) | coulomb | +04 9.648 70 |
| faraday (chemical) | coulomb | +04 9.649 57 |
| faraday (physical) | coulomb | +04 9.652 19 |
| fathom | meter | +00 1.828 8 |
| fermi (femtometer) | meter | −15 1.00 |
| fluid ounce (U.S.) | meter$^3$ | −05 2.957 352 |
| foot | meter | −01 3.048 |
| foot (U.S. survey) | meter | +00 1200/3937 |
| foot (U.S. survey) | meter | −01 3.048 006 |
| foot of water (39.2° F) | newton/meter$^2$ | +03 2.988 98 |
| foot-candle | lumen/meter$^2$ | +01 1.076 391 |
| foot-lambert | candela/meter$^2$ | +00 3.426 259 |
| furlong | meter | +02 2.011 68 |
| gal (galileo) | meter/second$^2$ | −02 1.00 |
| gallon (U.K. liquid) | meter$^3$ | −03 4.546 087 |
| gallon (U.S. dry) | meter$^3$ | −03 4.404 883 |
| gallon (U.S. liquid) | meter$^3$ | −03 3.785 411 |
| gamma | tesla | −09 1.00 |
| gauss | tesla | −04 1.00 |
| gilbert | ampere turn | −01 7.957 747 |
| gill (U.K.) | meter$^3$ | −04 1.420 652 |
| gill (U.S.) | meter$^3$ | −04 1.182 941 |
| grad | degree (angular) | −01 9.00 |
| grad | radian | −02 1.570 796 |
| grain | kilogram | −05 6.479 891 |
| gram | kilogram | −03 1.00 |
| hand | meter | −01 1.016 |
| hectare | meter$^2$ | +04 1.00 |
| henry (international of 1948) | henry | +00 1.000 495 |
| hogshead (U.S.) | meter$^3$ | −01 2.384 809 |
| horsepower (550 foot lbf/second) | watt | +02 7.456 998 |
| horsepower (boiler) | watt | +03 9.809 50 |
| horsepower (electric) | watt | +02 7.46 |
| horsepower (metric) | watt | +02 7.354 99 |
| horsepower (U.K.) | watt | +02 7.457 |
| horsepower (water) | watt | +02 7.460 43 |
| hour (mean solar) | second (mean solar) | +03 3.60 |
| hour (sidereal) | second (mean solar) | +03 3.590 170 |
| hundredweight (long) | kilogram | +01 5.080 234 |
| hundredweight (short) | kilogram | +01 4.535 923 |
| inch | meter | −02 2.54 |
| inch of mercury (32° F) | newton/meter$^2$ | +03 3.386 389 |
| inch of mercury (60° F) | newton/meter$^2$ | +03 3.376 85 |
| inch of water (39.2° F) | newton/meter$^2$ | +02 2.490 82 |
| inch of water (60° F) | newton/meter$^2$ | +02 2.4884 |
| joule (international of 1948) | joule | +00 1.000 165 |
| kayser | 1/meter | +02 1.00 |
| kilocalorie (International Steam Table) | joule | +03 4.186 74 |
| kilocalorie (mean) | joule | +03 4.190 02 |
| kilocalorie (thermochemical) | joule | +03 4.184 |
| kilogram mass | kilogram | +00 1.00 |

| To convert from | to | multiply by |
|---|---|---|
| kilogram force (kgf) | newton | +00 9.806 65 |
| kilopond force | newton | +00 9.806 65 |
| kip | newton | +03 4.448 221 |
| knot (international) | meter/second | −01 5.144 444 |
| lambert | candela/meter$^2$ | +04 $1/\pi$ |
| lambert | candela/meter$^2$ | +03 3.183 098 |
| langley | joule/meter$^2$ | +04 4.184 |
| lbf (pound force, avoirdupois) | newton | +00 4.448 221 |
| lbm (pound mass, avoirdupois) | kilogram | −01 4.535 923 |
| league (British nautical) | meter | +03 5.559 552 |
| league (international nautical) | meter | +03 5.556 |
| league (statute) | meter | +03 4.828 032 |
| light year | meter | +15 9.460 55 |
| link (engineer or ramden) | meter | −01 3.048 |
| link (surveyor or gunter) | meter | −01 2.011 68 |
| liter | meter$^3$ | −03 1.00 |
| lux | lumen/meter$^2$ | +00 1.00 |
| maxwell | weber | −08 1.00 |
| meter | wavelengths Kr 86 | +06 1.650 763 |
| micron | meter | −06 1.00 |
| mil | meter | −05 2.54 |
| mile (U.S. statute) | meter | +03 1.609 344 |
| mile (U.K. nautical) | meter | +03 1.853 184 |
| mile (international nautical) | meter | +03 1.852 |
| mile (U.S. nautical) | meter | +03 1.852 |
| millibar | newton/meter$^2$ | +02 1.00 |
| millimeter of mercury (0° C) | newton/meter$^2$ | +02 1.333 224 |
| minute (angle) | radian | −04 2.908 882 |
| minute (mean solar) | second (mean solar) | +01 6.00 |
| minute (sidereal) | second (mean solar) | +01 5.983 617 |
| month (mean calendar) | second (mean solar) | +06 2.628 |
| nautical mile (international) | meter | +03 1.852 |
| nautical mile (U.S.) | meter | +03 1.852 |
| nautical mile (U.K.) | meter | +03 1.853 184 |
| oersted | ampere/meter | +01 7.957 747 |
| ohm (international of 1948) | ohm | +00 1.000 495 |
| ounce force (avoirdupois) | newton | −01 2.780 138 |
| ounce mass (avoirdupois) | kilogram | −02 2.834 952 |
| ounce mass (troy or apothecary) | kilogram | −02 3.110 347 |
| ounce (U.S. fluid) | meter$^3$ | −05 2.957 352 |
| pace | meter | −01 7.62 |
| parsec | meter | +16 3.083 74 |
| pascal | newton/meter$^2$ | +00 1.00 |
| peck (U.S.) | meter$^3$ | −03 8.809 767 |
| pennyweight | kilogram | −03 1.555 173 |
| perch | meter | +00 5.0292 |
| phot | lumen/meter$^2$ | +04 1.00 |
| pica (printers) | meter | −03 4.217 517 |
| pint (U.S. dry) | meter$^3$ | −04 5.506 104 |
| pint (U.S. liquid) | meter$^3$ | −04 4.731 764 |
| point (printers) | meter | −04 3.514 598 |
| poise | newton second/meter$^2$ | −01 1.00 |
| pole | meter | +00 5.0292 |
| pound force (lbf avoirdupois) | newton | +00 4.448 221 |
| pound mass (lbm avoirdupois) | kilogram | −01 4.535 923 |
| pound mass (troy or apothecary) | kilogram | −01 3.732 417 |
| poundal | newton | −01 1.382 549 |
| quart (U.S. dry) | meter$^3$ | −03 1.101 220 |
| quart (U.S. liquid) | meter$^3$ | −04 9.463 529 |
| rad (radiation dose absorbed) | joule/kilogram | −02 1.00 |
| Rankine (temperature) | kelvin | $t_K = (5/9)t_R$ |
| rayleigh (rate of photon emission) | 1/second meter$^2$ | +10 1.00 |
| rhe | meter$^2$/newton second | +01 1.00 |
| rod | meter | +00 5.0292 |
| roentgen | coulomb/kilogram | −04 2.579 76 |
| rutherford | disintegration/second | +06 1.00 |
| second (angle) | radian | −06 4.848 136 |
| second (ephemeris) | second | +00 1.000 000 |
| second (mean solar) | second (ephemeris) | Consult American Ephemeris and Nautical Almanac |
| second (sidereal) | second (mean solar) | −01 9.972 695 |
| section | meter$^2$ | +06 2.589 988 |
| scruple (apothecary) | kilogram | −03 1.295 978 |
| shake | second | −08 1.00 |
| skein | meter | +02 1.097 28 |
| slug | kilogram | +01 1.459 390 |
| span | meter | −01 2.286 |
| statampere | ampere | −10 3.335 640 |
| statcoulomb | coulomb | −10 3.335 640 |
| statfarad | farad | −12 1.112 650 |
| stathenry | henry | +11 8.987 554 |
| statmho | mho | −12 1.112 650 |
| statohm | ohm | +11 8.987 554 |
| statute mile (U.S.) | meter | +03 1.609 344 |
| statvolt | volt | +02 2.997 925 |
| stere | meter$^3$ | +00 1.00 |
| stilb | candela/meter$^2$ | +04 1.00 |
| stoke | meter$^2$/second | −04 1.00 |
| tablespoon | meter$^3$ | −05 1.478 676 |
| teaspoon | meter$^3$ | −06 4.928 921 |
| ton (assay) | kilogram | −02 2.916 666 |
| ton (long) | kilogram | +03 1.016 046 |
| ton (metric) | kilogram | +03 1.00 |
| ton (nuclear equivalent of TNT) | joule | +09 4.20 |
| ton (register) | meter$^3$ | +00 2.831 684 |
| ton (short, 2000 pound) | kilogram | +02 9.071 847 |
| tonne | kilogram | +03 1.00 |
| torr (0° C) | newton/meter$^2$ | +02 1.333 22 |
| township | meter$^2$ | +07 9.323 957 |
| unit pole | weber | −07 1.256 637 |
| volt (international of 1948) | volt | +00 1.000 330 |
| watt (international of 1948) | watt | +00 1.000 165 |
| yard | meter | −01 9.144 |
| year (calendar) | second (mean solar) | +07 3.1536 |
| year (sidereal) | second (mean solar) | +07 3.155 815 |
| year (tropical) | second (mean solar) | +07 3.155 692 |
| year 1900, tropical, Jan., day 0, hour 12 | second (ephemeris) | +07 3.155 692 |
| year 1900, tropical, Jan., day 0, hour 12 | second | +07 3.155 692 |

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ACKNOWLEDGEMENT

The authors gratefully acknowledge the technical and management assistance provided by Lt. Cdr. Rodney L. Cook, Mr. David L. Motherway, Mr. Steven J. Rosenberg, and Dr. Leslie H. Chen of the Ocean Systems Branch, Coast Guard Research & Development Center. The assistance of the Coast Guard Atlantic, Pacific, and Gulf Strike Teams, and Mr. Steven C. Gibson of Rockwell EMSC is also acknowledged.

# 1. INTRODUCTION AND SUMMARY

In recent years, new methods have been developed for stopping the flow of hazardous materials spilling from ruptured or damaged containers. Work performed by Rockwell International in this area over the past years is described in a series of reports and papers listed in Refs. 1 through 10. Although excellent progress was made in developing a leak-plugging system using two-component foams, it was desired that additional exploratory work be performed to determine the feasibility of using alternative single-component foam systems. It was reasoned that should one prove feasible, an improved system would result, especially from an operational standpoint. The results of the most recent effort, Ref. 1, showed that a single-component foam is a feasible alternative to the dual-component foam as regards performance, while providing the obvious advantages of simplicity, low cost, and ease of use. In addition, a particular formulation of the single-component foam was tested successfully at low temperatures and at depth under water.

The present report describes work performed on Tasks 1, 2, 3, and 4 as proposed in Ref. 11 according to the following five-task program: Task 1 combines a design comparison and cost analysis with development of a buoyancy capability for a preprototype system which will be developed and tested, resulting in a final prototype design; Task 2 consists of design, construction, and checkout of a large-scale loading system for preparing and storing single-component foam; Task 3 comprises the construction and testing of eight leak-plugging systems based on the prototype design; Task 4 is an analytical evaluation of the feasibility of plugging larger holes with a single-component foam leak-plugging system; and Task 5 consists of the documentation summarizing the above work and includes the Task 1 Summary Report describing the final prototype design, which was subject to Coast Guard approval.

Subsequent to starting the program, Task 6 and Task 7 were added. Task 6 is a system integration study to develop an optimized shipping configuration, a manufacturing scenario analysis, a DOT exemption and a training program. Task 7 commenced following a change in Coast Guard project officers and consists of training Coast Guard project personnel in all aspects of the various leak-plugging systems. This report also contains conclusions and recommendations based on the data reported herein.

Eight prototypes of the external leak plugger have been fabricated and comprehensively tested, both in the laboratory and in the field, the latter by Coast Guard Strike Team divers. The reliability of the device has been amply verified. It has been used to adequately plug holes in tests beyond the design limits and within seconds of activation by an operator.

Aspects of satisfactory plug formation have been thoroughly investigated, resulting in dramatic improvements in the applicator tip design. A large-scale loading system for formulating significant quantities of polystyrene foam and for loading individual devices with the premixed foam has been developed and used, resulting in a considerable saving of time over the technique employed previously.

A large plug feasibility study has shown no insurmountable engineering problems precluding the development and use of a scaled-up leak-plugging system. A detailed analytical investigation of sizing requirements, loading requirements, and environmental considerations has produced a recommended system configuration with a high probability for system success.

A system integration study has furthered the production and deployment of the external leak plugger by selecting the optimum leak plugger shipping configuration, determining the most cost-effective approach for producing the external leak plugger in quantity, filing a formal application with the DOT for exempting the loaded device from certain shipping regulations, and preparing a training program, including a narrated color film and a slide presentation, to train the Strike Team divers in the proper use and operation of the external leak plugger.

Coast Guard project personnel have received in-depth training regarding all aspects of the external leak plugger, its fabrication, loading, and operation.

## 2. TECHNICAL EFFORT

### 2.1 BACKGROUND

Rockwell, under EPA and Coast Guard sponsorship, has successfully conducted an effort over a number of years to develop a prototype system for plugging leaking chemical containers. Initially, the feasibility of controlling spills by the application of suitable plastic barriers was demonstrated. Building on the feasibility demonstration, a program was performed successfully to develop and test a prototype system for temporarily stopping the flow of hazardous materials spilling from ruptured or damaged containers. The prototype system was portable, integrated, and field-operable by one man. It used foamed in-place polyurethane rigid foam plugs surrounded by a flexible protective membrane for sealing leaks. One problem with the system as developed was the temperature requirement for effective foam formation. The minimum operable temperature was about 280 K (45 F). This lower temperature limitation would restrict the applicability of the leak-plugging system when used underwater. The work of these programs is described in published papers and reports (Refs. 2 - 10).

A subsequent effort for the Coast Guard (Ref. 1) was undertaken in which various alternative methods for plugging leaks in hazardous chemical containers utilizing rigid foam generating techniques were evaluated. Exploratory research was conducted to determine whether a particular, unique single-component foam-generating technique would be applicable. Experimentation and preliminary design work showed that a feasible system could be built and that such a system would have a number of advantages when compared with earlier methods. Some recognized advantages were the inherent simplicity of the single-component foam system and the convenient form of the foam tank, which can also be used as a handle for inserting the applicator tip into the hole to be plugged. It was recommended that the single-component foam system be further pursued as the prime candidate for a leak-plugging system of this type. Additional evidence obtained from tests conducted at the Coast Guard Research and Development Center indicated the feasibility of using single-component polystyrene foams for plugging holes at low ambient temperatures and for underwater use at depth.

This report describes work performed under Modifications 4, 5, 6, 7, and 8 of Contract DOT-CG-81-78-1817, entitled the Foam Plug Development Program, and covers the period January 1979 to December 1979.

The objectives of the Foam Plug Development Program are to improve the existing leak-plugging system, designed for plugging underwater holes up to 0.1 meter (4 inches) in diameter, and to modify it to satisfy the requirements for use by Coast Guard pollution response personnel.

The program involves seven tasks which consist of developing a prototype leak-plugging system design, constructing a large-scale loading system, fabricating eight prototype leak-plugging systems for delivery, preparing an analytical feasibility evaluation for plugging larger holes, conducting a system integration study, training Coast Guard project personnel, and developing a final report detailing the above work.

## 2.2 PREPROTOTYPE DEVELOPMENT

Before a prototype leak plugger could be developed in earnest, certain technical specifications of the system had to be characterized. This was accomplished by the design, construction, and testing of a preprototype system which included a cost analysis of a reusable system versus a throwaway system, the development of a buoyancy package for the system, and finalization of a prototype design.

### 2.2.1 Experimental Design

The major proposed design specifications for the preprototype leak-plugging system are as follows:

1. The designs will be complete enough to permit a detailed cost analysis and a comparison to be made between a reusable system and a throwaway system (see Appendix A).
2. The selected design shall provide close to neutral buoyancy of the combined charged delivery system (lance) and applicator tip before use, and slightly positive buoyancy of the spent delivery lance after use.

3. The selected system shall be designed so that it is compatible with and can be loaded from a large reservoir of premixed single-component foam.

4. Provision will be made in the system design to allow for ease of handling, delivery, and activation by a diver.

5. The selected design shall also provide for a shelf life of at least one year.

A sketch of the preprototype leak-plugging system design appears in Fig. 1. Parts numbered in the figure are listed and described in detail in Table 1. The experimental foam delivery system consists of three major subsystems: the applicator tip, the lance, and the pressurant assembly.

The applicator tip consists of a hardware assembly and an outer fabric covering. The hardware assembly provides the required connection to a foam-containing lance, directs the incoming foam in a suitable pattern and provides the internal support for the outer fabric. The hardware assembly was based on two different Coast Guard designs and comprised some of their best features. (An important consideration in redesigning the applicator tip was the desire to reduce the cost of machining the hardware.) The hardware assembly is constructed of Items 1, 4, 5, and 7, machined from aluminum specifically for reuse purposes during preprototype testing. (Note: Although aluminum is expressly prohibited from use as a material of construction in the lance [Ref. 12], it is not precluded from use in the applicator tip due to the extremely short exposure times of the applicator tip to the liquid foam.) The hardware is covered with a fabric, 3, tailored in a cylindrical shape and held on by a hose clamp, 6.

The lance, containing the polystyrene foam mixture between rupture discs located inside burst disc assemblies 10 and 16, is attached to the applicator tip by a Kamlok coupling assembly, 8 and 9. Attached externally to the lance is the foam buoyancy package, 13, designed to provide neutral buoyancy to the charged delivery system before use and slightly positive buoyancy following use. The umbilical filling port, 11, as shown

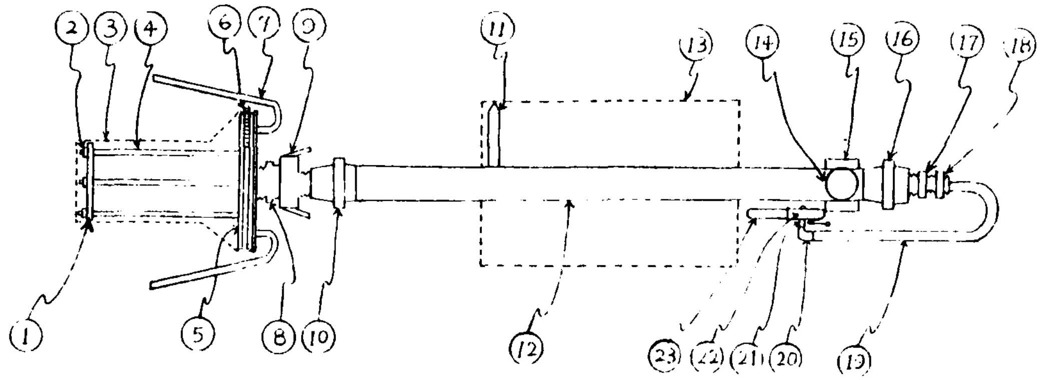

Figure 1. Preprototype Leak-Plugging System (see Table 1)

in Fig. 1, is crimped and sealed when the lance has been loaded with the polystyrene foam mixture.

The pressurant assembly contains a carbon dioxide ($CO_2$) gas cartridge, 23, which provides the driving force when the operator trips the firing mechanism on the inflator, 22, allowing $CO_2$ gas to flow into the $CO_2$ expansion tube, 19. A fitting with an orifice, 18, (part of the lance subsystem) controls the rate of $CO_2$ gas flow into the lance so that destructive flowrates will be avoided. The experimental leak-plugging system is designed so that once the major subsystems are connected and the system is armed with a $CO_2$ cartridge, the underwater operator will be able to fire the system by a single motion, that of tripping the firing mechanism in the pressurant assembly. The rest of the operation will proceed automatically.

The required buoyancy package was determined through use of the buoyancy correction equations found in Table 2 and the calculated results were developed from the weight and volume data listed in Table 1. The buoyancy of the spent delivery lance will vary depending on the amount of water that enters the cavity following foam expulsion, but in no case will the effective system density be greater than 1.

TABLE 1. PREPROTOTYPE DELIVERY SYSTEM COMPONENT DETAILS

| Item No.[a] | Item Name | Manufacturer or Supplier | Part No. | Size and Type Connection | Weight[b], kg | Approximate Volume[b], $m^3 \times 10^5$ | Cost[c], Dollars |
|---|---|---|---|---|---|---|---|
| | Applicator Tip [d] | | | | | | |
| 1 | Applicator tip disc | | | | | | |
| 2 | 10-32 nuts | | | | | | |
| 3 | Applicator fabric | | | | | | |
| 4 | Applicator tip rod | Local hardware store and in-house fabrication | | | 0.460 | 31.0 | 70.00 |
| 5 | Applicator tip disc | | | | | | |
| 6 | Applicator fabric clamp | | | | | | |
| 7 | Spacer rods | | | | | | |
| 8 | Kamlok adaptor | Dover Corp., OPW Division Cincinnati, OH | 633-F, Al | 0.019 m (3/4") | 0.028 | 3.3 | 2.35 |
| | Lance | | | | | | |
| 9 | Kamlok coupler | Dover Corp., OPW Division Cincinnati, OH | 633-B, Br | 0.019 m (3/4") | 0.198 | 7.3 | 5.60 |
| 10 | a) Fike burst disc assembly | Fike Metal Products Corp. Blue Springs, MO | EU, SS | 0.019 m (3/4") | 0.394 | 8.8 | 84.53 (57.78) |
| | b) Rupture disc | Fike Metal Products Corp. Blue Springs, MO | $2.07 \times 10^6$ Pa (300 psi) Ni | 0.019 m (3/4") | -- | -- | 13.11 |
| 11 | Filling port | Tubesales, Los Angeles, CA | 304 SS | 0.0095 m OD x 0.30 m L x 0.0007 m W (3/8" OD x 12" L x 0.028" W) | 0.080 | 2.2 | 2.00 |
| 12 | Foam tank | Tubesales, Los Angeles, CA | 304 SS | 0.025 m OD x 0.86 m L x 0.0012 m W (1" OD x 34" L x 0.049" W) | 0.656 | 43.7 | 16.43 (7.88) |
| 13 | Buoyancy package | Thorpe Insulation Co., Los Angeles, CA | Foamglas | 0.038 m thick x 0.30 m L (1½" thick x 12" L) | 0.310 | 224.0 | 4.00 |
| 14 | Chrome steel ball | McMaster-Carr, Los Angeles, CA | 9528K32 | 0.022 m (7/8") dia | 0.045 | 0.6 | 2.40 |
| 15 | Magnet | McMaster-Carr Los Angeles, CA | 5841K13 | Series P, Alnico 5 | 0.105 | 1.6 | 4.32 |
| 16 | a) Fike burst disc assembly | Fike Metal Corp., Blue Springs, MO | CU,SS | 0.019 m (3/4") | 0.394 | 8.8 | 77.24 (57.78) |
| | b) Rupture disc | Fike Metal Corp., Blue Springs, MO | $2.07 \times 10^6$ Pa (300 psi) Ni | 0.019 m (3/4") | -- | -- | 13.11 |
| 17 | SS Busning | Airdrome, Long Beach, CA | AN912-7J | 0.019 m NPT x 0.013 m NPT (3/4" NPT x 1/2" NPT) | 0.060 | 0.3 | 2.85 |
| 18 | SS Nipple with orifice | Airdrome, Long Beach, CA | AN816-4-8J | 0.013 m NPT x 0.006 m NPT (½" NPT x ¼" NPT) | 0.070 | 0.3 | 10.00 |
| | Pressurant Assembly | | | | | | |
| 19 | $CO_2$ expansion tube | Tubesales, Los Angeles, CA | 304 SS (plus B-nuts and sleeves) | 0.006 m OD x 0.51 m L x 0.0009 m W (¼" OD x 20" L x 0.035" W) | 0.087 | 1.6 | 5.00 (3.50) |
| 20 | SS elbow, swivel | Airdrome, Long Beach, CA | 4CEX SS | 0.006 m F-AN to 0.006 m M-AN (¼" F-AN to ¼" M-AN) | 0.033 | 0.3 | 4.64 |
| 21<br>22 | Inflator stem<br>Inflator | Sparklet Devices, St. Louis, MO | A-136 | Threaded | 0.100 | 2.0 | 6.00 |
| 23 | $CO_2$ cartridge | Sparklet Devices, St. Louis, MO | 237S | 0.016 kg, net wt | 0.060 | 2.0 | 1.28 |

a - See Fig. 1.

b - Used to develop buoyancy corrections in Table 2.

c - Used to develop Cost Analysis (see Appendix); ($) refer to carbon steel items used in throwaway system.

d - The applicator tip hardware assembly was designed for reuse during preprototype testing.

TABLE 2. BUOYANCY PACKAGE CALCULATIONS[a]

| Item No. | Item Name | Fresh Water | Salt Water |
|---|---|---|---|
| 1 | Equation for Calculation[b] (in SI units) | $\frac{W_S + \rho_B V_B}{V_S + V_B} = 1000$ | $\frac{W_S + \rho_B V_B}{V_S + V_B} = 1035$ |
| 2 | Required Buoyancy Correction | $V_B = 0.00224\ m^3$ ($137\ in^3$) | $V_B = 0.00211\ m^3$ ($129\ in^3$) |
| 3 | Density of Spent Delivery Lance | 0.85 - 0.97 | 0.88 - 1.0 |
| 4 | Amount of Material of Buoyancy Package | (a) 0.038-m (1.5 inch) thickness of FOAMGLAS Length: 0.3 m (12") | (a) 0.038-m (1.5-inch) thickness of FOAMGLAS Length: 0.28 m (11") |
| | | (b) 0.025-m (1") thickness of FOAMGLAS Length: 0.56 m (22") | (b) 0.025-m (1") thickness of FOAMGLAS Length: 0.51 m (20") |

a - Based on information listed in Table 1, which includes weight and volume estimates provided by manufacturers and suppliers.

b - With: $W_S$: Weight of System; $V_S$: Volume of System; $\rho_B$: Density of Buoyancy Package; $V_B$: Volume of Buoyancy Package

2.2.2. Preliminary Testing

While preprototype leak plugger design and fabrication were progressing, construction and checkout of the new large-scale foam loading system (Section 2.4) and experimental testing of applicator tip fabrics proceeded. The purpose of the latter tests was to identify the fabric that could most suitably be adapted to the leak-plugging assignment. Potential applicator tip coverings were examined in the event that materials currently in use proved to be of insufficient strength to contain the 2XF polystyrene foam mixture (see Section 2.4.3). Not only was a fabric study important in terms of developing an applicator tip worthy of incorporation in a final, viable leak-plugging system, but it was also imperative that the applicator tip be sufficiently reliable so that subsequent testing of the preprototype lance design would truly reflect the merits of the lance design and not the applicator tip.

The preliminary testing involved the plugging of 0.1-m (4-inch), irregularly shaped holes at room temperature in air using two of the old-style lances depicted in Fig. 2. (For a detailed description of the old-style lance and its operation, see Ref. 1.) The following three fabrics were tested: a government-issued Neoprene-coated, knitted stretch nylon fabric, a vinyl auto upholstery fabric, and a duckbill polyester sailcloth fabric. They range, as listed, from elastic to inelastic in stretching quality. All applicator fabrics were tailored to a cylindrical shape with single-stitched seams of nylon thread and then capped on one end with similar fabric.

The relatively inelastic fabrics were configured so the applicator tips would be able to contain the maximum quantity of foam chemicals for any and all conditions determined by the parametric study. The elastic nylon fabric was configured smaller in diameter in the expectation that it would expand to accommodate the maximum quantity of foam chemicals, an advantage which would enable it to plug a wider variety of hole sizes.

The first tests, which utilized a nominal composition foam mixture (see Section 2.4.3) and which are described in Table 3, showed that the rather inelastic fabrics, the vinyl upholstery (T2, Fig. 3) and the sailcloth (T3, Fig. 4), fared considerably better than the elastic Neoprene-coated nylon fabric. The latter usually ruptured (T5, Fig. 5) or exhibited

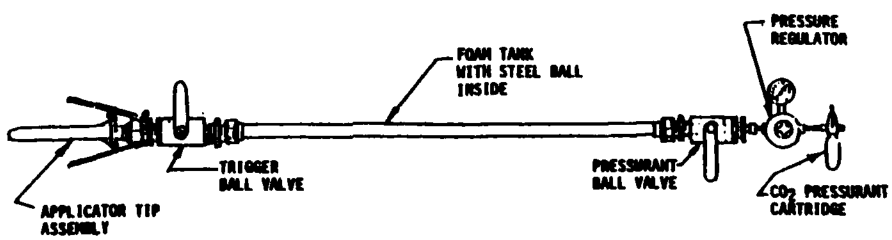


Figure 2. Old-Style Lance Delivery System

TABLE 3. EFFECT OF APPLICATOR FABRIC ON PLUGGING 0.1-METER (4-INCH) HOLES USING A POLYSTYRENE FOAM MIXTURE[a]

| Test Designation | Fabric Material | Fabric Dimensions | Foam Wt, kg | Hole Plug | Plug Description |
|---|---|---|---|---|---|
| T1-GFL-LH | Knitted Stretch Nylon | 0.076 m Dia x 0.030 m L (3" Dia x 12" L) w/longitudinal elastic vector | 0.388 | No | Ruptured on seam (near side), very little foam on far side |
| T2-AFL-LH | Vinyl Upholstery | 0.15 m Dia x 0.30 m L (6" Dia x 12" L) | 0.335 | Yes | Larger sphere on far side, smaller sphere on near side |
| T3-SFL-LH | Polyester Sailcloth | 0.15 m Dia x 0.30 m L (6" Dia x 12" L) | 0.337 | Yes | Large cylinder on far side, same diameter sphere on near side |
| T4-GFL-LH | Knitted Stretch Nylon | 0.076 m Dia x 0.30 m L (3" Dia x 12" L) w/longitudinal elastic vector | 0.333 | No | Ruptured on seam (near side), very little foam on far side |
| T5-GFSR-SH | Knitted Stretch Nylon | 0.076 m Dia x 0.20 m L (3" Dia x 8" L) w/radial elastic vector | 0.287 | No | Ruptured on near side |
| T6-AFL-LH[b] | Vinyl Upholstery | 0.15 m Dia x 0.30 m L (6" Dia x 12"L) | 0.313 | Yes | Larger sphere on far side, smaller sphere on near side |
| T7-GFLR-LH | Knitted Stretch Nylon | 0.13 m Dia x 0.30 m L (5" Dia x 12" L) w/radial elastic vector | 0.292 | No | Very large sphere on near side (seam shows signs of tearing), very little foam on far side |

a - All tests were conducted using the old-style lances and, except for T6, all were conducted in air at room temperature; foam used was nominal composition mixture A1-N.

b - This test was conducted under water at 288 K (59 F) with an immersion time of 5 minutes.

an expansion of the plug on the near side that rendered the plug essentially useless (T7, Fig. 6). It is believed that this effect is due to the elasticity of the fabric, which provides very little resistance to radial foam expansion, while axial foam expansion is inhibited by the solidifying foam near the constriction formed by the hole being plugged. With inelastic fabrics, the fabric structure limits radial expansion, thereby promoting greater axial expansion.

Following the above tests, which were designed not just to provide data on applicator fabrics, but also on the reliability of the large-scale loading system, a second set of tests was conducted to provide information

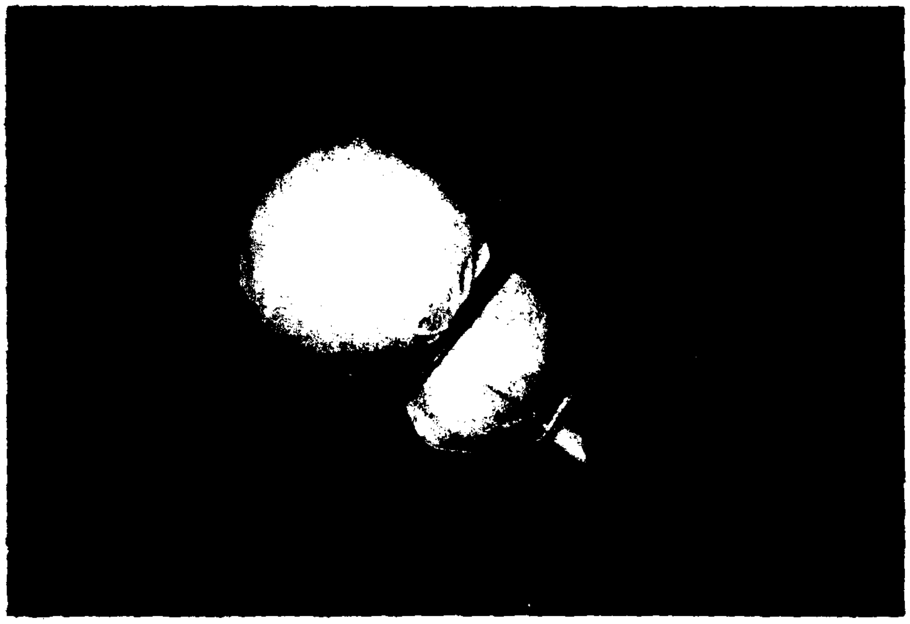

Figure 3. Test T2 Plug Showing Vinyl Upholstery Fabric in Use

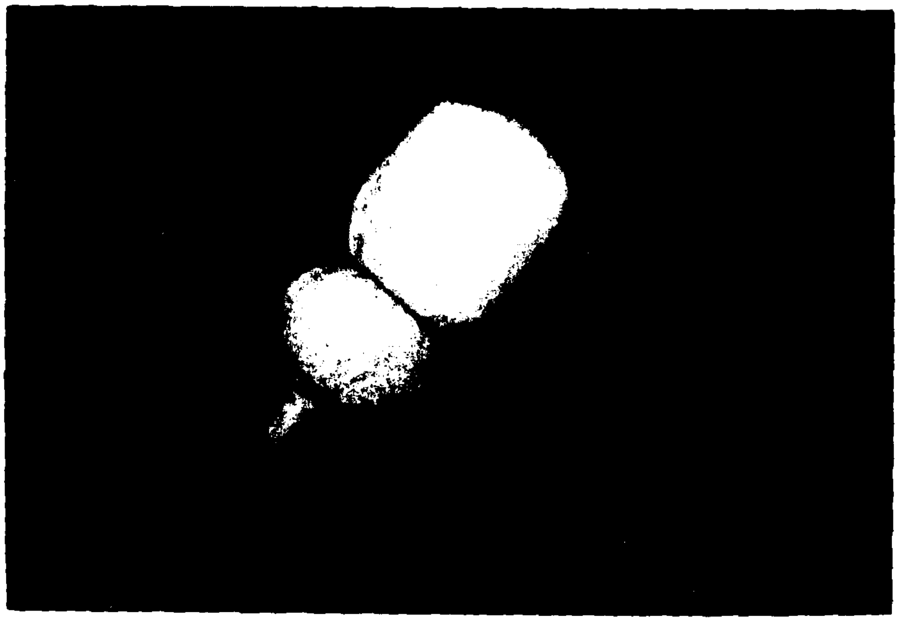

Figure 4. Test T3 Plug Showing Polyester Sailcloth Fabric in Use

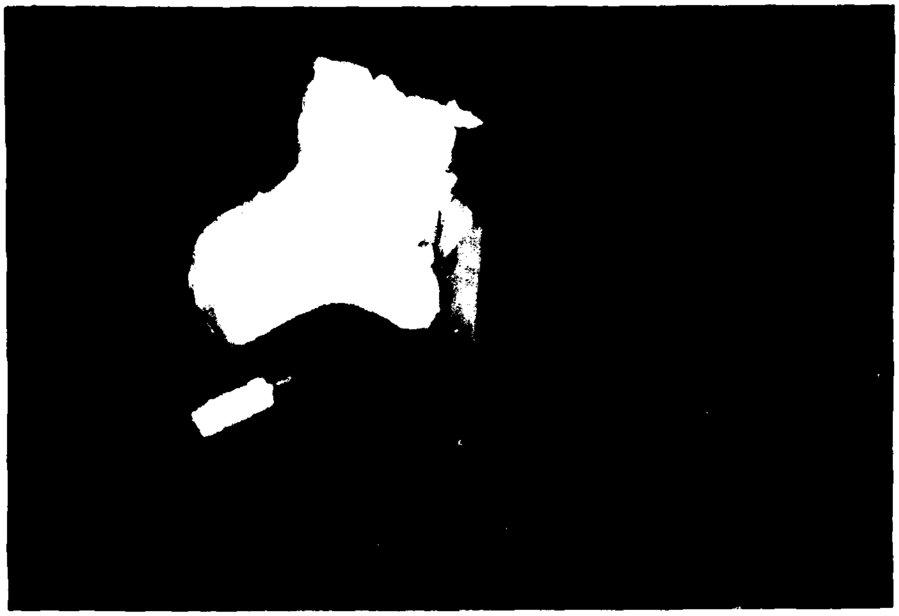

Figure 5. Test T5 Plug Showing Rupture of Knitted Stretch Nylon Fabric

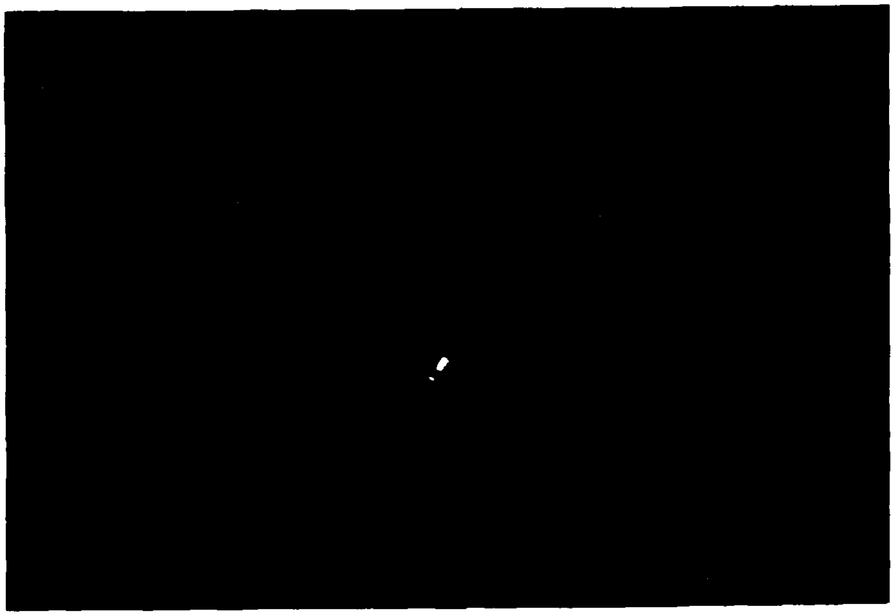

Figure 6. Test T7 Plug Removed From Target and Showing Negligible Plug Formation on Far Side

on the effect of applicator tip modifications on foam plug formation and on the loading and plugging characteristics of the 2XF foam mixture. The data from these tests are found in Table 4. It was hoped that certain changes could easily be made to the applicator hardware to eliminate the problem experienced with the elastic fabric over-expanding on the near side. A tough aluminum tape was tried first. The tape was wrapped around the three applicator connecting rods for a distance of 0.076 to 0.10 meter (3 to 4 inches) from the large aluminum disc. When the effectiveness of the tape appeared uncertain, a more durable PVC tube was used to divert the foam from the front to the rear of the applicator tips. An examination of Tests T8 and T15 show that this modification produced a definite improvement. Although a foam diverter appears to be a necessity in the formation of successful plugs using elastic fabrics, its importance in the formation of inelastic fabric plugs is somewhat less significant. Nevertheless, the foam diverter was felt worthy of incorporation in the applicator tip design and, therefore, all subsequent tests have used tips with this modification. Another decision based on the above test results was that of conducting the contractually required underwater preprototype tests with the vinyl upholstery fabric because of its good plug-forming and waterproof characteristics. The sailcloth fabric formed, perhaps, even better plugs in the air, but the fabric is not waterproof. However, the treated sailcloth fabric was tested further during subsequent preprototype testing.

### 2.2.3. Preprototype Testing

The preprototype lance delivery system, depicted in Fig. 7, experienced certain subtle changes after the original experimental design was first proposed. These included the employment of the aforementioned foam diverter in the applicator tip and the use of the $CO_2$ inflator manifold stem as the orifice for restricting $CO_2$ gas flow. Since the manifold stem is manufactured with a very fine orifice, it was appropriate to conduct the first preprototype lance tests using it, rather than a separate flow restrictor downstream of the $CO_2$ expansion tube, to restrict gas flow.

TABLE 4. EFFECT OF APPLICATOR TIP ON PLUGGING 0.1-METER (4-INCH) HOLES USING 2XF FOAM MIXTURE [a]

| Test Designation | Fabric Material | Fabric Dimensions [b] | Foam Diverter | Foam Wt, kg | $CO_2$ Pressure, Pa (psi) | Hole Plug | Plug Description |
|---|---|---|---|---|---|---|---|
| T8-GFSR-SH | Knitted Stretch Nylon | A | -- | 0.128 | $1.14 \times 10^6$ (150) | No | Ruptured on seam (near side), not much foam on far side |
| T9-AFL-LH | Vinyl Upholstery | B | -- | 0.270 | $1.14 \times 10^6$ (150) | Yes | Large irregular cylinder on far side (75 v/o), same diameter sphere on near side (25 v/o) |
| T10-SFL-LH | Polyester Sailcloth | B | -- | 0.284 | $1.14 \times 10^6$ (150) | Yes | Large sphere on near side (60 v/o), smaller sphere on far side (40 v/o) |
| T11-GFLR-LH | Knitted Stretch Nylon | B | -- | 0.328 | $1.48 \times 10^6$ (200) | No | Ruptured on seam (near side), very little foam on far side |
| T12-SFL-LH | Polyester Sailcloth | B | Wrapped Al Tape | 0.297 | $1.48 \times 10^6$ (200) | Yes | Large irregular cylinder on far side (75 v/o), same diameter sphere on near side (25 v/o) |
| T13-AFL-LH | Vinyl Upholstery | B | Wrapped Al Tape | 0.268 | $1.48 \times 10^6$ (200) | Yes | Large irregular sphere on far side (75 v/o), smaller sphere on near side (25 v/o) |
| T14-GFLR-LH | Knitted Stretch Nylon | B | Wrapped Al Tape | 0.291 | $1.48 \times 10^6$ (200) | No | Large sphere on near side, very little foam on far side |
| T15-GFSR-SH | Knitted Stretch Nylon | A | PVC Tube [c] | 0.149 | $1.48 \times 10^6$ (200) | Yes | Irregular sphere on far side (60 v/o), sphere on near side (40 v/o) |

a - All tests were conducted in air at room temperature using the old-style lance; foam used was mixture A2-2XF.

b - Fabric dimensions used were: A, 0.076-m (3-inch) Dia x 0.20-m (8-inch) L; and B, 0.15-m (6-inch) Dia x .030-m (12-inch) L.

c - The PVC tube was dimensioned 0.038-m (1-1/2-inch) Dia x 0.05-m (2-inch) L.

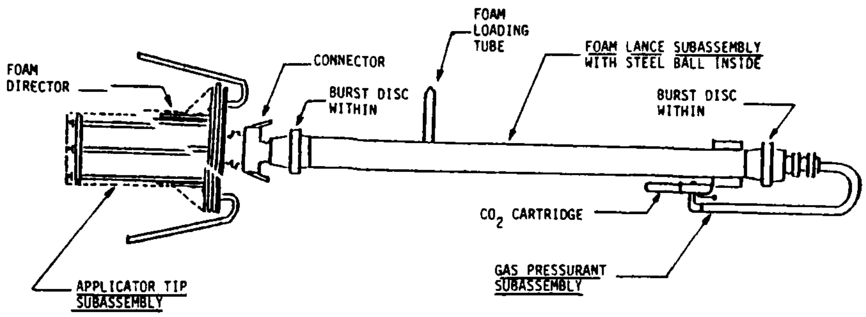


Figure 7. Preprototype Lance Delivery System (buoyancy package not shown)

Results of the first tests of the preprototype lance appear in Table 5. The data provided the first indication that the manifold stem flow restrictor is adequate and that the burst disc assembly concept and the rupture disc arrangement are satisfactory for leak-plugging applications.

2.2.3.1 Laboratory Testing

Underwater testing of the preprototype lance was conducted in the laboratory and the results appear in Table 6. These tests were conducted in a water trough with the water either at room temperature or at temperatures close to the icewater point with varying lance and applicator tip immersion times. Almost all test applicator tips used the vinyl upholstery fabric. The vinyl upholstery fabric, previously shown as having the most desirable qualities of any tested fabric, possesses considerable structural strength, an essential feature, and, except for the tailored seams, is very waterproof. To waterproof the seams, applications on the seams of various special coatings were made and the coated fabrics were tested. These test results also appear in Table 6. The applicator tip hardware assembly used connecting rods, between the front and rear aluminum discs,

TABLE 5. INITIAL PREPROTOTYPE LANCE TESTING[a]

| Designation | Fabric Material | Plug Description | $CO_2$ Wt, kg | Foam Wt, kg |
|---|---|---|---|---|
| PT1-SF | Sailcloth | Large cylinder on far side, smaller sphere on near side | 0.026 | 0.308 |
| PT2-AF | Upholstery | Large cylinder on far side, smaller sphere on near side | 0.026 | 0.317 |
| PT3-SF | Sailcloth | Large cylinder on far side, smaller sphere on near side | 0.016 | 0.320 |

a - All tests were conducted in air at room temperature using applicator tips with fabrics tailored to 0.15-m (6-inch) dia x 0.30-m (12-inch) L, with PVC foam diverters machined to 0.038-m (1-1/2-inch) dia x 0.076-m (3-inch) L, and with three spacer rods; the applicator tip connecting rods separated the applicator discs by 0.23 meter (9 inches). The foam used was nominal composition mixture A3-N and the hole size used was a 0.10-m (4-inch), irregularly shaped circle.

which produced a disc-to-disc separation of 0.23 meter (9 inches).

Expulsion times were about 1 to 2 seconds for the room-temperature tests and approximately 4 seconds for the low-temperature tests. No detectable difference in results was observed between use of the 0.016 kg (.035 lb) net weight $CO_2$ cartridge and the 0.026 kg (.057 lb) net weight $CO_2$ cartridge. Expulsion efficiencies were determined by lance weighings before and after expulsion, while plug density was obtained by calculating the amount of solid present in the expelled foam (from foam mix ingredient data) and the volume of the foam plug formed (from foam plug size measurements). Although determined by a different technique, the listed plug densities are quite similar to those reported in Ref. 13, wherein a cube of the foam plug is cut out to known dimensions (assuming a representative sampling) and weighed.

Several observations can be drawn from the data in Table 6. One is that the vinyl upholstery applicator tip fabric used is very forgiving. Although designed for loadings of approximately 0.30 kg (0.66 lb) of 2XF foam, the actual loadings varied from a low of 0.27 kg (0.60 lb) to a high of 0.365 kg

## TABLE 6. UNDERWATER LABORATORY TESTS OF PREPROTOTYPE LANCE[a]

| Test Designation | Special Coating(s) | Immersion Time | | Temperature, °K (°F) | $CO_2$ Wt, kg | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, kg/m³ (lbm/ft³) |
|---|---|---|---|---|---|---|---|---|
| | | Lance, Hrs | Applicator, Mins | | | | | |
| Foam Mixture A3: | | | | | | | | |
| PT4-SF | Rubber Sleeve | 1.0 | 1 | 292 (66) | 0.026 | 0.313 | 90[b] | -- |
| PT5-AF | None | 1.5 | 1 | 292 (66) | 0.026 | 0.317 | 90[b] | -- |
| PT6-AF | None | 1.3 | 1 | 290 (63) | 0.026 | 0.313 | 90[b] | -- |
| PT7-AF | None | 2.5 | 1 | 276 (37) | 0.026 | 0.300 | 90[b] | -- |
| Foam Mixture A4: | | | | | | | | |
| PT8-AF | None | 1.5 | 1 | 276 (37) | 0.026 | 0.310 | 91 | 33.2 (2.2) |
| PT9-AF[c] | None | 1.5 | 1 | 289 (60) | 0.026 | 0.270 | 90 | 30.4 (1.9) |
| PT10-AF[d] | None | 1.5 | 1 | 289 (60) | 0.026 | 0.311 | 92 | 30.4 (1.9) |
| PT11-AF | None | 4.5 | 1 | 290 (62) | 0.025 | 0.303 | 91 | 28.8 (1.8) |
| PT12-SF | Entire fabric, Thompson's Water Seal | 4.75 | 1 | 290 (62) | 0.026 | 0.313 | 90 | 32.0 (2.0) |
| PT13-AF | Seam and Disc, Permatex #2 | 4.75 | 30 | 289 (60) | 0.016 | 0.297 | 87 | 25.6 (1.6) |
| PT14-AF | Seam and Disc, Permatex #1 | 5.0 | 40 | 289 (60) | 0.016 | 0.337 | 89 | 33.6 (2.1) |
| PT15-AF[e] | None | 1.25 | 1 | 290 (63) | 0.016 | 0.307 | 88 | 22.4 (1.4) |
| Foam Mixture A5: | | | | | | | | |
| PT16-AF | Seam, Gasket-Cinch; Disc, PVC | 3.75 | 50 | 273 (32) | 0.016 | 0.278 | 86 | 44.8 (2.8) |
| PT17-AF | Seam, Nitrile Rubber; Disc, PVC | 4.0 | 70 | 273 (32) | 0.016 | 0.278 | 84 | 36.8 (2.3) |
| PT18-AF | Seam, PVC; Disc, Permatex #1 | 6.5 | 40 | 273 (32) | 0.016 | 0.317 | 88 | 30.4 (1.9) |
| PT19-AF | Seam, Silicone Rubber; Disc, Permatex #2 | 6.5 | 50 | 273 (32) | 0.026 | 0.279 | 88 | 38.4 (2.4) |
| PT20-AF | Seam and Disc, Silicone Rubber | 2.25 | 60 | 276 (37) | 0.016 | 0.270 | 85 | 27.2 (1.7) |
| PT21-AF | Seam and Disc, Silicone Rubber | 2.25 | 60 | 276 (37) | 0.016 | 0.327 | 88 | 32.0 (2.0) |
| Foam Mixture B1: | | | | | | | | |
| PT22-AF[d] | Seam and Disc, Silicone Rubber | 1.25 | 25 | 276 (37) | 0.016 | 0.365 | 93 | 36.8 (2.3) |
| PT23-AF | Seam, Permatex #2; Disc, Silicone Rubber | 0.75 | 25 | 276 (37) | 0.016 | 0.316 | 91 | 36.8 (2.3) |
| PT24-AF[f] | Seam, Permatex #1; Disc, Silicone Rubber | [illegible].85 | 1 | 276 (37) | 0.016 | 0.233 | -- | -- |
| PT25-AF | Seam, PVC; Disc, Silicone Rubber | 3.85 | 40 | 276 (37) | 0.016 | 0.321 | 90 | 46.4 (2.9) |
| PT26-AF | Seam, PVC; Disc, Silicone Rubber | 4.25 | 1 | 276 (37) | 0.016 | 0.315 | 89 | 33.6 (2.1) |

a - All tests were conducted in a water trough using 0.1-meter (4-inch), irregularly shaped circular holes, except as noted, and all holes were plugged successfully (except for PT-24) using 2XF foam mixtures. All test systems used applicator tips with vinyl upholstery fabric (except PT4 and PT12 which used sailcloth) tailored to 0.15-m (6-inch) dia x 0.30-m (12-inch) L, with PVC foam diverters machined to 0.038-m (1-1/2-inch) dia x 0.076-m (3-inch) L, and with three spacer rods apiece. The applicator tip connecting rods separated the applicator discs by 0.23 meter (9 inches).

b - These expulsion efficiencies were not determined from the usual lance weighings; the calculations were based on foam composition and plug weighings.

c - Hole plugged was .13-m (5-inch), irregularly shaped circle.

d - Hole plugged was .15-m (6-inch), irregularly shaped circle.

e - Hole plugged was .10 x .20 m (4 x 8 inch), irregularly shaped oval.

f - This test was unsuccessful due to the failure of the first or rear rupture disc to break.

(0.80 lb), almost a 0.1 kg (0.22 lb) difference. This is equivalent to a variation of ±15% based on a loading of 0.317 kg (0.70 lb). Yet, all expulsions formed adequate, or better, foam plugs with no fabric ruptures, a remarkable achievement. Just as remarkable is the observation that the external leak plugger can not only plug 0.1-m (4-inch) holes (Fig. 8), for which it was designed, but also can satisfactorily plug 0.13-m (5-inch) (Fig. 9), 0.15-m (6-inch) (Fig. 10), and 0.1 x 0.2-m (4 x 8-inch) (Fig. 11) irregularly shaped holes, demonstrating the system's versatility in plugging a wide range of hole sizes.

Another item of note is that Test PT4 shows the sailcloth fabric can be adapted for underwater use by enclosing it in a rubber sleeve. The sleeve burst, as expected, during the operation as the pressure of exuding vapors reached its burst pressure, yet it adequately fulfilled its purpose of temporarily waterproofing the sailcloth fabric.

The waterproof seam coating was intended as a temporary measure to prevent water from entering the applicator tip before the lance was fired. Upon expulsion of the foam from the lance and its subsequent outgassing within the applicator tip, the seam coating was expected to break away, allowing the vapors to vent through the fabric seam. Applicator immersion times up to 70 minutes have been attempted with these coatings applied to the fabric seams and the resultant foam plugs have been successful (see Figs. 12 through 15). Of all the seam coating materials tried, silicone rubber exhibited the most desirable qualities.

A conclusion that can be reached from a study of the data is that expulsion efficiency, determined by lance weighings before and after foam expulsion, is directly related to the rate at which the foam is expelled. In other words, a slower expulsion rate provides the foam with greater time for solidification, thereby increasing the resistance to further expulsion of additional foam quantities from the lance. As can be seen from Table 6, the following factors, in general, increase the rate of expulsion and, therefore, the expulsion efficiency: higher temperatures which cause lower foam viscosities, higher foam loadings which result in smaller ullage volumes, and

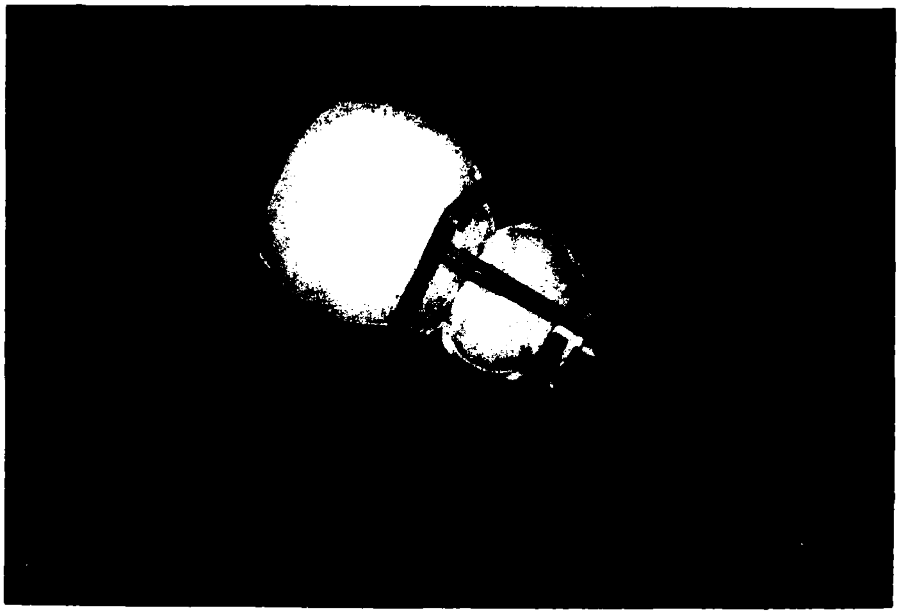

Figure 8. Test PT11 Plug in 0.1-m (4-inch) Target Hole

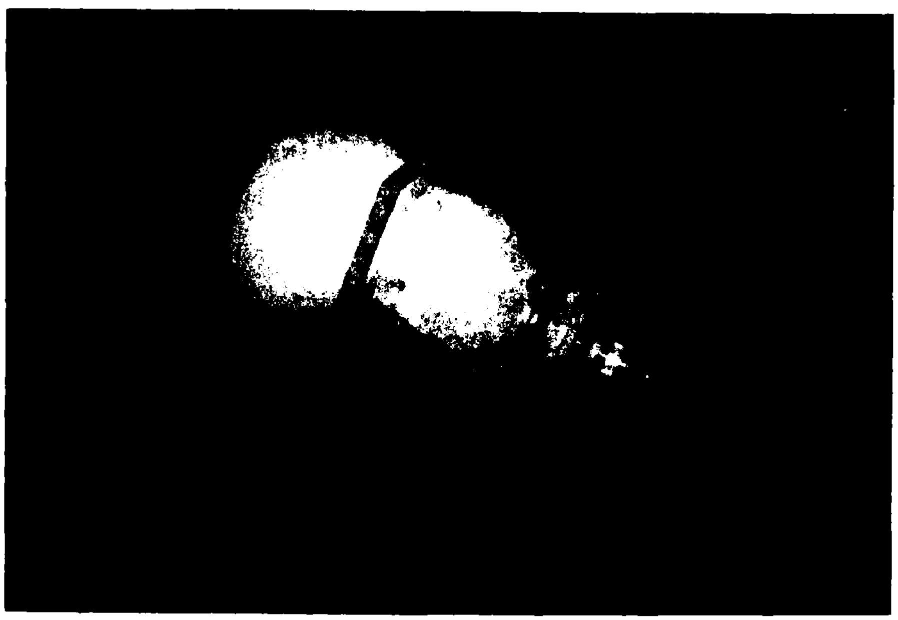

Figure 9. Test PT9 Plug in 0.13-m (5-inch) Target Hole

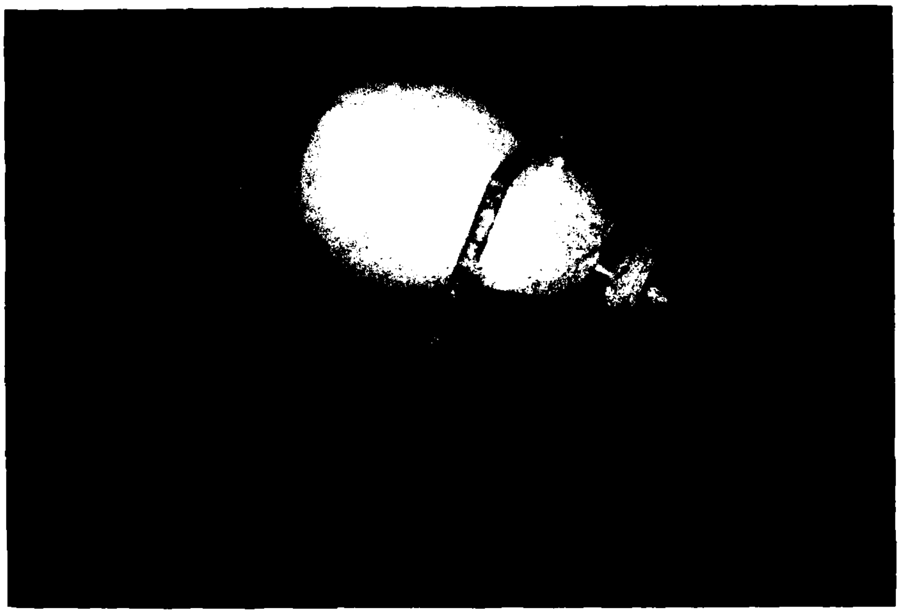

Figure 10. Test PT10 Plug in 0.15-m (6-inch) Target Hole

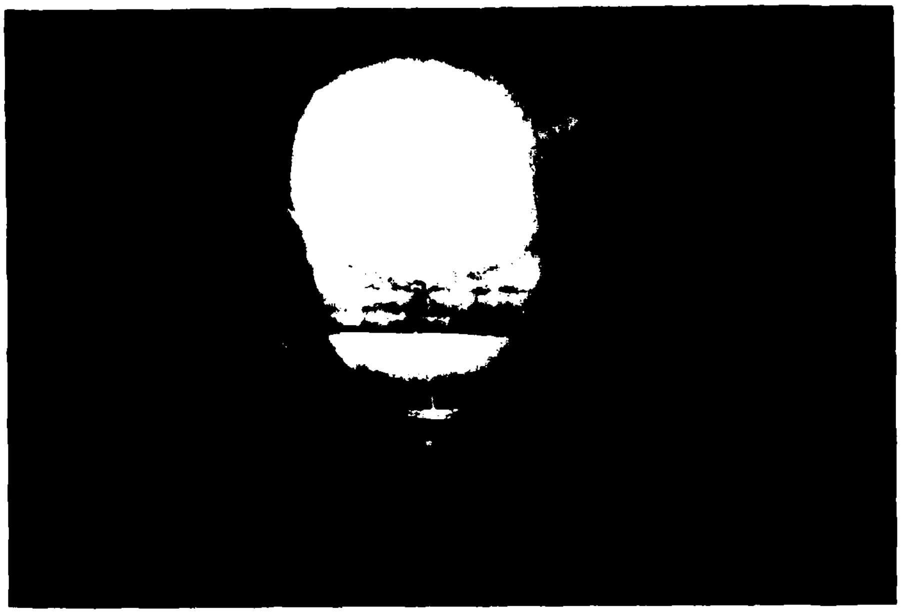

Figure 11. Test PT15 Plug in 0.1 x 0.2-m (4 x 8-inch) Target Hole

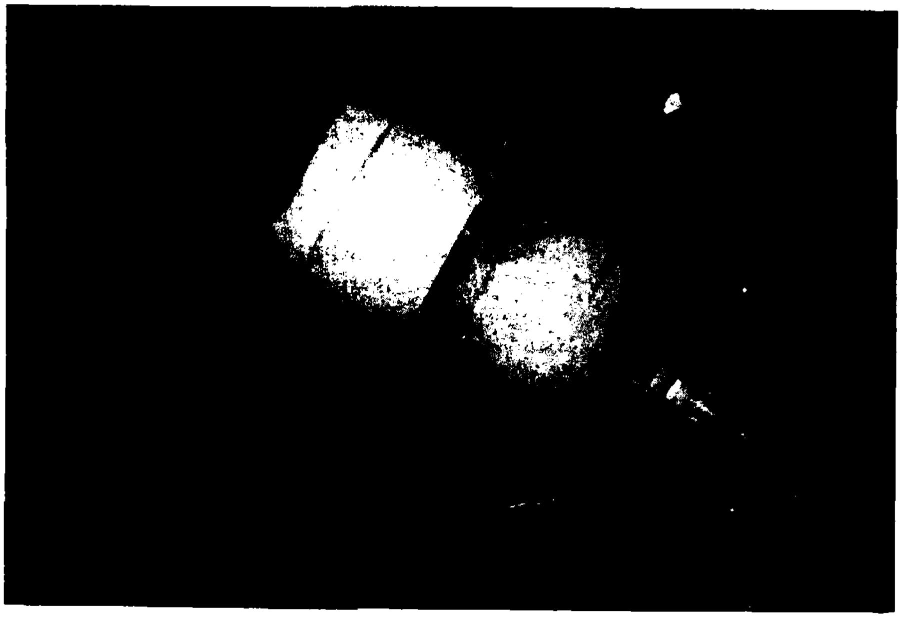

Figure 12. Test PT13 Plug Showing Permatex #2 Coating on Seam

Figure 13. Test PT14 Plug Showing Permatex #1 Coating on Seam

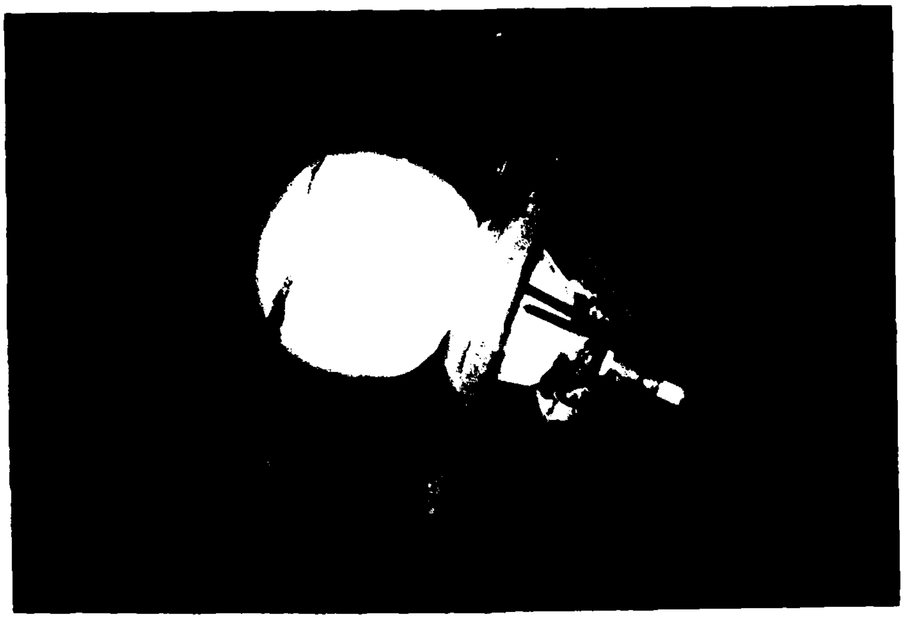

Figure 14. Test PT19 Plug Showing Silicone Rubber Coating on Seam

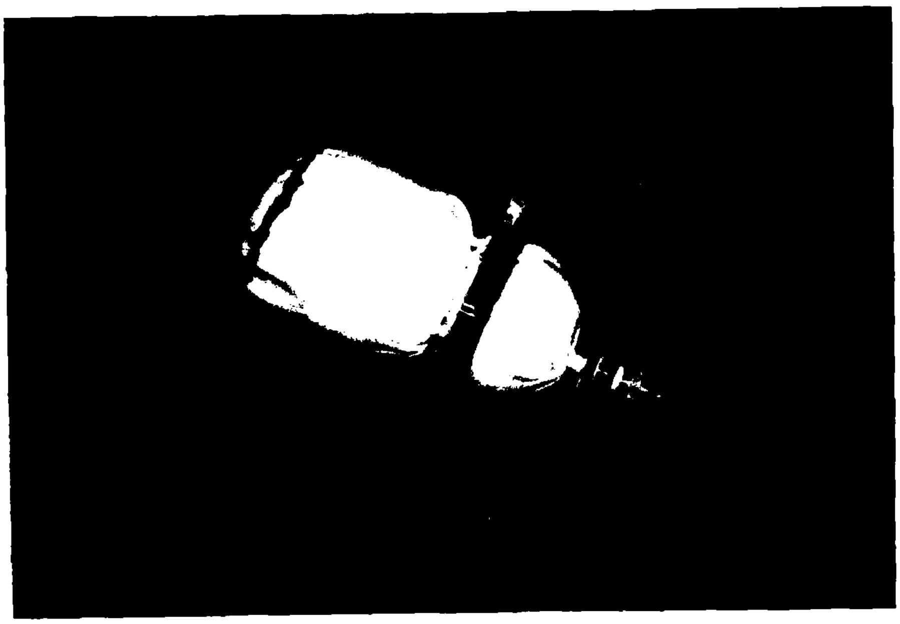

Figure 15. Test PT26 Plug Showing PVC Coating on Seam

larger $CO_2$ cartridges which provide quicker attainment of the $CO_2$ vapor pressure. It should be noted that although expulsion efficiencies varied, in percentage, from the mid-80s to the low 90s, no significant difference in foam plugs was attributable to this variation.

All of the underwater laboratory tests of the preprototype lance formed successful plugs, save one. That singular test was PT24, which failed when the first or rear rupture disc did not break despite two attempts with separate $CO_2$ cartridges. To investigate this unusual behavior, the liquefied foam was expelled through the loading port and the lance was disassembled for inspection. The rear rupture disc exhibited definite signs of having been stressed; many small wrinkles were evident throughout the thin piece of metal. Upon consultation with the manufacturer, it was concluded that the vacuum support was prevented from peeling back by the bore of the welding holddown and, thereby, continued supporting the rupture disc. Since the rear rupture disc and vacuum support, during foam expulsion, have to flex back in the direction opposite that in which they are normally expected to be overpressurized, the vacuum support petal achieves a diameter slightly larger than the ID of the welding holddown section of the burst disc assembly. The vacuum support, therefore, can potentially be mechanically supported by the inside lip of the welding holddown. To eliminate this problem, the inside diameter of the welding holddown was machined larger on all existing test lances. Of course, for a test to have failed, other contributing factors, such as low temperature and commensurate low $CO_2$ vapor pressure, may also have contributed. Nevertheless, with only one failure experienced in 23 tests, a highly commendable success ratio of 96 percent was achieved.

2.2.3.2 Field Testing

Underwater tests of the preprototype leak-plugging system in a private swimming pool were conducted to check out the device under field conditions and to photograph the system under those operating conditions using an underwater 16mm movie camera. A team of professional photographers performed the latter function. More than 200 meters (650 feet) of raw film footage was

obtained, processed, and edited. This footage was combined with additional footage taken at EMSC to produce an 11-minute, narrated color film showing the external leak plugger, its components and subassemblies, the leak-checking and foam-loading operations, the testing of the device underwater in the laboratory and the operation of it by a certified scuba diver in the private swimming pool. Several prints were made and delivered to the Coast Guard for training purposes. The data from the pool tests appear in Table 7.

For the tests, a special target was fabricated of 0.013-m (1/2-inch) plywood and mounted on a Unistrut assembly. Ten holes of various sizes and irregular shapes were cut out of the target which was weighted down to counteract the buoyancy effect as selected holes were plugged. As can be seen from the data, all attempts, except FPT 6, formed successful foam plugs. As an example, the plug formed on test FPT 5 can be seen in Figs. 16 and 17. The $CO_2$ inflator malfunctioned in the unsuccessful test, resulting in a foam plug which foamed (expanded and solidified) while the inflator was being inspected on the deck of the pool. Evidence suggested that the firing pin stuck in the $CO_2$ cartridge, when the cartridge was punctured, and was released only when the cartridge was being unscrewed from the inflator. This problem was eliminated by coating the firing pin with a suitable lubricant.

Buoyancy packages for the preprototype lance were also investigated during the underwater pool tests. The 0.025-m (1-inch) thick x 0.60-m (24-inch) long Foamglas package proved inadequate, while the 0.038-m (1-1/2-inch) thick x 0.60-m (24-inch) long package provided the loaded delivery system with too much buoyancy for the scuba diver to handle. In light of this, the buoyancy correction for the preprototype system was recalculated based on actual hardware weights and volumes (see note "a" in Table 2) to determine the minimum buoyancy package required for fresh water. Using the equation described in Table 2, the revised buoyancy correction was calculated to be $3.21 \times 10^{-3}$ $m^3$ (196 $in^3$), providing an explanation for the observed buoyancy package testing results. In addition, the updated correction equates to an uncoated Foamglas buoyancy package of 0.038-m (1.5-

TABLE 7. UNDERWATER POOL TESTS OF PREPROTOTYPE LEAK-PLUGGING SYSTEM[a]

| Test Designation | Buoyancy Package [b] | Hole Shape/ Hole Size, m (in.) | Plug Description | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, kg/m$^3$ (lbm/ft$^3$) |
|---|---|---|---|---|---|---|
| Foam Mixture A5: | | | | | | |
| FPT 1 | A | Circle/0.10 (4) | Good, large (far) and small (near) spheres | 0.255 | 88 | 30 (1.9) |
| FPT 2 | A | Circle/0.13 (5) | Good, large (far) and small (near) spheres | 0.290 | 90 | 29 (1.8) |
| Foam Mixture A6: | | | | | | |
| FPT 3 | A | Square/0.13 (5) | Good, large (far) and small (near) spheres | 0.327 | 89 | 32 (2.0) |
| FPT 4 | B | Circle/0.10 (4) | Good, large (far) and small (near) spheres | 0.295 | 89 | 29 (1.8) |
| FPT 5 | B | Circle/0.13 (5) | Good, large (far) and small (near) spheres | 0.335 | 92 | 29 (1.8) |
| FPT 6 | B | Square/0.13 (5) | $CO_2$ inflator malfunctioned, cartridge fired with system on deck | 0.343 | 91 | 24 (1.5) |

a - All tests were conducted in a private swimming pool by certified Rockwell divers. All test systems were loaded with 2XF foam mixtures and all applicator tips consisted of the usual hardware and vinyl upholstery fabric tailored to 0.15-m (6-inch) dia x 0.30-m (12-inch) L and coated on the seams and at the disc with silicone rubber. The test temperature averaged 297 K (75 F).

b - Buoyancy package dimensions used were: A, 0.025-m (1-inch) thick x .060-m (24-inch) L; and B, 0.038-m (1-1/2-inch) thick x 0.60-m (24-inch) L.

inch) thick x 0.41-m (16-inch) long. However, to assure a spent delivery lance with a total buoyancy sufficient to raise it to the water surface for retrieval, an empirical approach was followed. In the subsequent Strike Team field tests, the 0.038-m (1-1/2-inch) thick Foamglas package was shortened to 0.53-m (21-inches) long and tested underwater for diver maneuverability, with tremendous success.

To further evaluate the preprototype leak-plugging system, the device was used in a series of underwater tests on May 30-31 conducted by members of the Coast Guard Strike Teams with the assistance of the Rockwell project team. The results of these tests, conducted in a private swimming pool,

Figure 16. Test FPT-5 Plug (Front View) Showing Silicone Rubber Partially Rolled Away From Seam

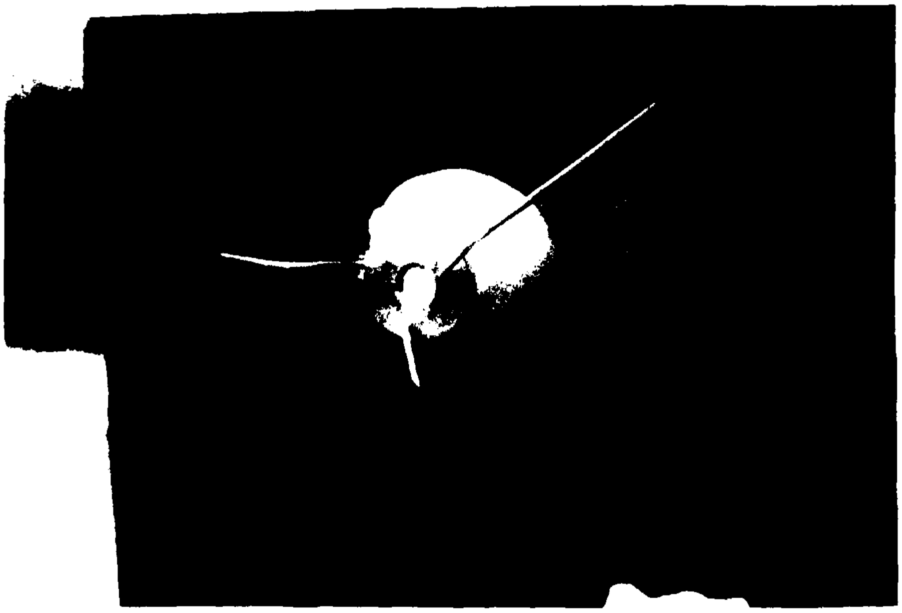

Figure 17. Test FPT-5 Plug (Rear View) Showing Silicone Rubber and Adjacent, Lengthwise Seam

appear in Table 8. During these tests the preprototype leak plugger was put through a very rigorous testing matrix by a group of professional Coast Guard divers selected from the Atlantic, Pacific, and Gulf Strike Teams. To simulate some of the most demanding field conditions, the divers purposely restricted their physical abilities while using the preprototype leak plugger. In every case, a foam plug was formed which would have blocked 95 percent or more of the target hole.

Tests STPT 5 and STPT 6 (Figs. 18 and 19) demonstrated the successful use of the external leak plugger in an interesting and novel application, namely, the plugging of an elongated hole through the consecutive use of two or more of the leak-plugging devices. Although two of the applicator fabrics (STPT 7 and STPT 8) did rupture, they did so during attempts to plug holes well beyond the design limits and yet the foam plugs still appeared adequate for the job. An important aspect of this testing was the vital feedback from the divers regarding the operator/device interface. Many helpful suggestions for minor modifications to the device were received and incorporated into the prototype design. The divers expressed their satisfaction with the operation of the device.

## 2.3 PROTOTYPE DEVELOPMENT

As a result of the preprototype testing phase, a final prototype design of the external leak plugger was developed. (See Fig. 20.) The lance delivery system consists of a foam-containing lance and a gas pressurant assembly. The storage or containment system involves a metal tube with a burst disc assembly attached to each end. Within each burst disc assembly is a rupture disc predesigned to break away at a given pressure. The driving force for the transfer or expulsion function is provided by carbon dioxide from an ordinary $CO_2$ gas cartridge located in the gas pressurant assembly. When firing the device, a firing mechanism punctures the gas cartridge, releasing $CO_2$ gas which feeds into the lance, breaking the rupture discs and expelling

TABLE 8. UNDERWATER STRIKE TEAM TESTS OF PREPROTOTYPE LEAK-PLUGGING SYSTEM[a]

| Test Designation | Diver Restriction | Hole Shape/ Hole Size, m (in) | Plug Description | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, kg/m$^3$ (lbm/ft$^3$) |
|---|---|---|---|---|---|---|
| STPT 1 | None | Circle/0.06 (2½) | Good, large (far) and small (near) spheres | 0.220 | 86 | 22 (1.4) |
| STPT 2 | None | Circle/0.10 (4) | Good, large (far) and small (near) spheres | 0.288 | 91 | 26 (1.6) |
| STPT 3 | Blindfolded with gloves | Circle/0.13 (5) | Good, large (far) and small (near) spheres | 0.314 | 91 | 26 (1.6) |
| STPT 4 | One-armed | Square/0.13 (5) | Good, large (far) and small (near) spheres | 0.321 | 91 | 24 (1.5) |
| STPT 5 | Without visor | Rectangle/ 0.10 x 0.30 (4 x 12) | Good, large (far) and small (near) cylinders | 0.320 | 92 | 26 (1.6) |
| STPT 6 | None | Rectangle/ 0.10 x 0.30 (4 x 12) | Good, large (far) and small (near) cylinders | 0.328 | 91 | 26 (1.6) |
| STPT 7 | Blindfolded with gloves | Circle/0.20 (8) | Adequate, bag ruptured on seam (near and far) | 0.370 | 93 | 19 (1.2) |
| STPT 8 | Blindfolded and one-armed | Rectangle/ 0.10 x 0.20 (4 x 8) | Adequate, bag ruptured on seam (far) | 0.354 | 92 | 21 (1.3) |

a - All tests were conducted in a private swimming pool by Coast Guard Strike Team divers. All test systems were loaded with the foam mixture B1-2XF, and all applicator tips consisted of the usual hardware and vinyl upholstery fabric tailored to 0.15-m (6-inch) dia x 0.30-m (12-inch) L and coated on the seams and at the front disc with silicone rubber. The test temperature averaged 297 K (75 F).

the fluid foam. The applicator tip assembly provides the means by which the foam can be contained for the purpose of plugging ruptures or holes. It consists of a hardware assembly and an outer tailored fabric. The hardware assembly directs the incoming fluid in a particular pattern, as well as provides the applicator tip with a basic structure for attaching to the lance delivery system. The tailored fabric, because of its flexibility, is reduced to the approximate size of the hardware assembly by being folded into pleats, before use, and, upon introduction of fluid, expands to its originally tailored dimensions.

Figure 18. Tests STPT 5 and 6 Plugs (Front View) Shown Plugging Portion of Elongated Target Hole

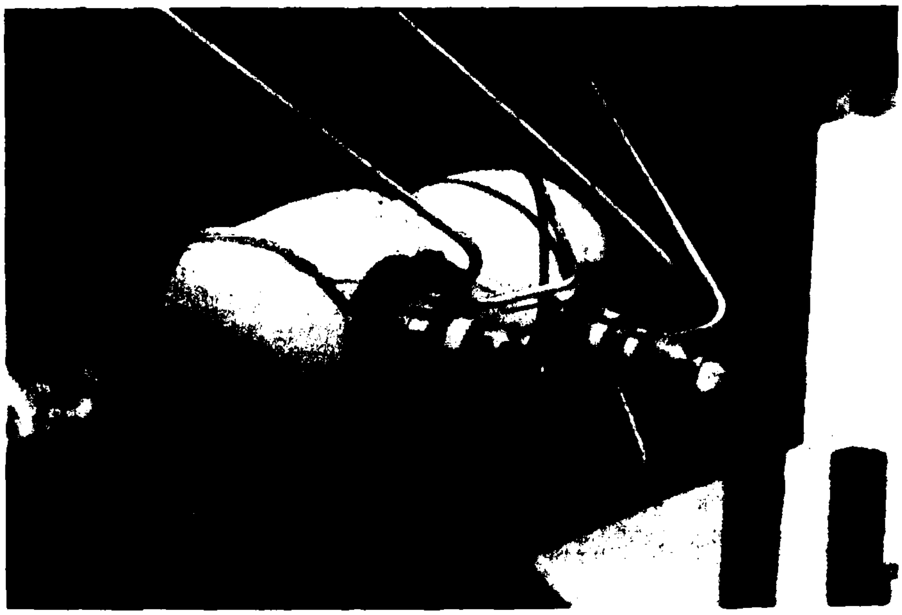

Figure 19. Tests STPT 5 and 6 Plugs (Rear View) in Elongated Target Hole

## 2.3.1 Prototype Design

The prototype design incorporates refinements proposed by members of the Coast Guard R&D Center, the Coast Guard Strike Teams, and Rockwell's EMSC. The basic assemblies and certain important features are listed in Fig. 20. New modifications, such as a special T-bar firing mechanism, a split buoyancy package, thumb tabs on the Kamlok connector arms, and a relocated, smaller loading port, are included. Another sketch of the prototype leak-plugging system appears in Fig. 21, which, together with Table 9, provides a much more detailed description of the final concept.

The foam-containing lance is assembled with a $2.17 \times 10^6$ pascals (300 psi) rupture disc and a vacuum support disc in each burst disc assembly. It is leak-checked with $1.48 \times 10^6$ pascals (200 psi) of helium using a gas leak detector and then loaded with methyl chloride vapor prior to loading with a premixed polystyrene foam formulation. (The polystyrene formulation is prepared in accordance with a Monsanto Corporation formula that involves dissolving a given quantity of solid polystyrene in methyl chloride, a liquefied compressed gas, followed by the addition of Freon 13B1, another compressed gas which serves as a blowing agent. For additional details, see Section 2.4.3.) The foam formulation is loaded under pressure by means of a unique foam transfer system connected to the lance through a filling port. When it is determined that the desired amount of foam has been loaded, the loading tube is crimped off and silver-brazed. Tests have shown that the loaded lance can be stored in this configuration for months without any measureable loss of its contents (Section 2.3.2.3).

The applicator tip assembly consists of a hardware assembly and a fabric assembly. The hardware assembly, depicted in Fig. 22, consists of two discs, one larger than the other, attached together by three metal rods. Connected to the larger disc is a foam diverter, which directs the incoming foam to the front of the applicator tip where the smaller disc directs the foam in a radial pattern. The hardware is covered with a vinyl upholstery fabric, which is tailored to specific dimensions as indicated under New Reversed" fabric design in Section 2.3.2.1. The fabric assembly is

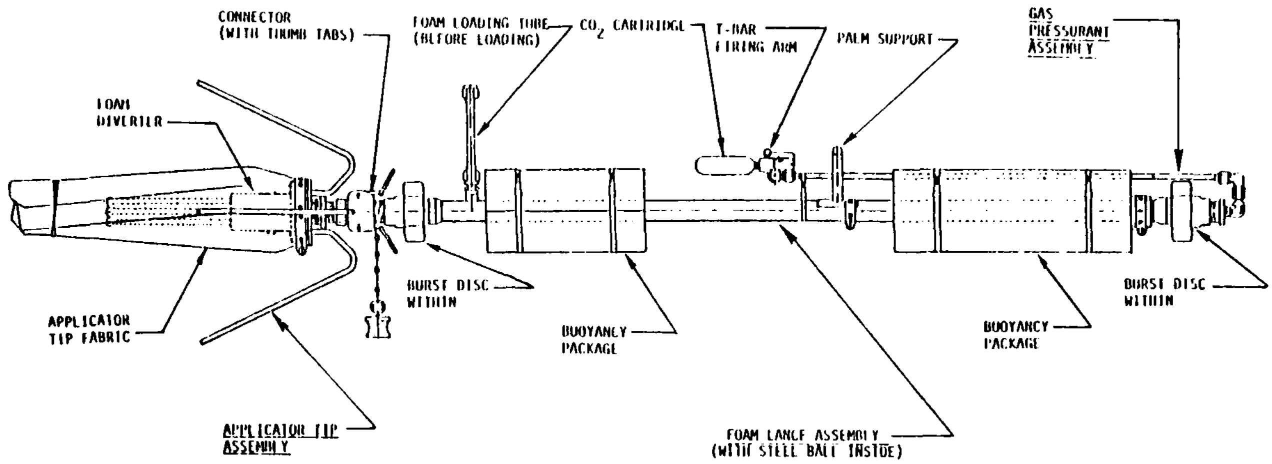


Figure 20.  Prototype External Leak Plugger

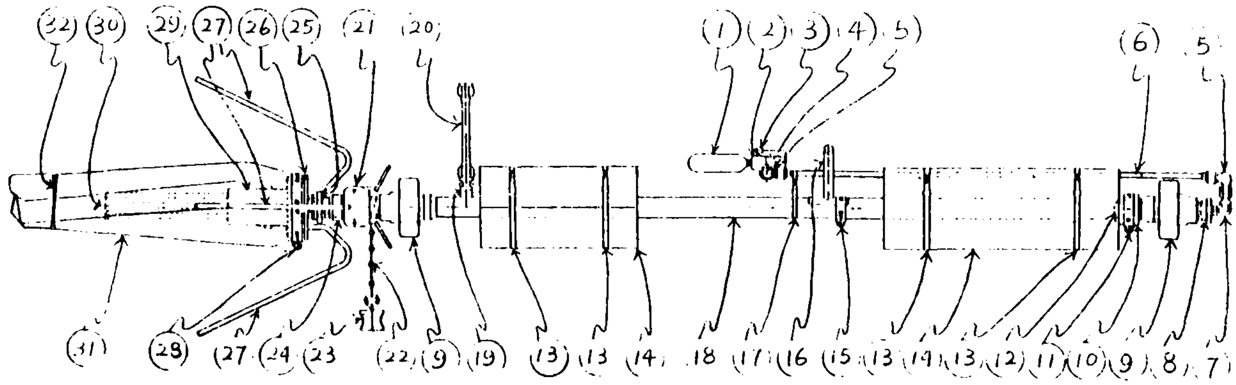

Figure 21.  Prototype External Leak Plugger Detail
(See Table 9)

TABLE 9. PROTOTYPE LEAK-PLUGGING SYSTEM COMPONENT DETAILS (Sheet 1 of 2)

| Item No. | Item Name | Manufacturer or Supplier | Part No. | Size and Type Connector |
|---|---|---|---|---|
| | Gas Pressurant Assembly | | | |
| 1 | $CO_2$ Cartridge | Sparklet Devices, St. Louis, MO | 237S | 0.016 kg, net |
| 2 | Inflator | Sparklet Devices, St. Louis, MO | A-136 | Threaded |
| 3 | T-bar firing arm | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.0095 m OD x 0.064 m L (3/8" OD x 2½" L) |
| 4 | a) Inflator cap nut | Halkey Roberts, Paramus, NJ | 833-A0E | |
| | b) Inflator stem | Sparket Devices, St. Louis, MO | A36-133 | |
| | c) O-ring | Parker Seal Co., Culver City, CA | 2-004, V747-75 | |
| | d) Union | Airdrome, Long Beach, CA | AN815-4J | |
| 5 | Elbow, swivel, SS | Airdrome, Long Beach, CA | AP262 -4J | 0.006 m F-AN to 0.006 m M-AN (¼" F-AN to ¼" M-AN), 2 required |
| 6 | a) $CO_2$ expansion tube | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.006 m OD x 0.56 m L x 0.0009 m W (¼" OD x 22" L x 0.035" W) |
| | b) Sleeves | Airdrome, Long Beach, CA | MS20819-4J | 0.006 m (¼"), 2 required |
| | c) Coupling nut | Airdrome, Long Beach, CA | AN818-4J | 0.006 m (¼"), 2 required |
| | Foam Lance Assembly | | | |
| 7 | Elbow, SS | Airdrome, Long Beach, CA | MS20822-4-4J | 0.006 m NPT x 0.006 m AN (¼" NPT x ¼" AN) |
| 3 | Bushing, SS | Airdrome, Long Beach, CA | AN912-7J | 0.019 m NPT x 0.006 m NPT (3/4" NPT x 1/4" NPT) |
| 9 | a) Fike burst disc assembly | Fike Metal Products Corp. Blue Spring, MO | EU, $20.8 \times 10^6$ Pa (3000 psi), SS | 0.019 m (3/4"), 2 required |
| | b) Rupture disc | Fike Metal Products Corp. Blue Spring, MO | Standard, $2.17 \times 10^6$ Pa (300 psi), nickel | 0.019 m (3/4"), 2 required |
| | c) Vacuum support disc | Fike Metal Products Corp. Blue Spring, MO | Standard, nickel | 0.019 m (3/4"), 2 required |
| 10 | Magnet | McMaster-Carr, Los Angeles, CA | 5841K13 | Series P Alnico 5 |
| 11 | Clamp | Ryan Herco, Burbank, CA | 0950-020 | |
| 12 | Ball, chrome steel | McMaster-Carr, Los Angeles, CA | 9528K32 | 0.022 m (7/8") dia |
| 13 | Cable tie | Cole-Parmer Instrument Co., Chicago, IL | 6830-35 | 4 required |
| 14 | a) Buoyancy package, rear | Thorpe Insulation Co., Los Angeles, CA | Foamglas w/3M protective coating 1706 | 0.038 m thick x 0.30 m L (1½" thick x 12" L) |
| | b) Buoyancy package, front | Thorpe Insulation Co., Los Angeles, CA | Foamglas w/3M protective coating 1706 | 0.038 m thick x 0.20 m L (1½" thick x 8" L) |
| 15 | Clamp | Ryan Herco, Burbank, CA | 0950-012 | |
| 16 | a) Horizontal tube | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.013 m OD x 0.051 m L (½" OD x 2" L) |
| | b) Vertical tube | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.013 m OD x 0.064 m L (½" OD x 2½" L) |
| | c) Saddle | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.025 m OD x 0.051 m L (1" OD x 2" L) |
| 17 | Cable tie | Cole-Parmer Instrument Co. Chicago, IL | 6830-30 | |
| 18 | Foam tank | Tubesales, Los Angeles, CA | 304 SS | 0.025 m OD x 0.91 m L x 0.0012 m W (1" OD x 36" L x 0.049" W) |
| 19 | Fitting | Airdrome, Long Beach, CA | AN816-6J | 0.0095 m NPT x 0.0095 m AN (3/8" NPT x 3/8" AN) |

TABLE 9. PROTOTYPE LEAK-PLUGGING SYSTEM COMPONENT DETAILS (Sheet 2 of 2)

| Item No. | Item Name | Manufacturer or Supplier | Part No. | Size and Type Connector |
|---|---|---|---|---|
| 20 | a) Filling tube | Tubesales, Los Angeles, CA In-house fabrication | 304 SS | 0.0095 m OD x 0.10 m L x 0.0007 m W (3/8" OD x 4" L x 0.028" W) |
| | b) Sleeves | Airdrome, Long Beach, CA | MS20819-6J | 0.0095 m (3/8"), 2 required |
| | c) Coupling nut | Airdrome, Long Beach, CA | AN818-6J | 0.0095 m (3/8"), 2 required |
| 21 | Kamlok coupler (mod.) | Dover Corp., OPW Division Cincinnati, OH | 633B Bronze | 0.019 m (3/4") |
| 22 | Chain | Local hardware store | Brass | |
| 23 | Kamlok plug | Dover Corp., OPW Division Cincinnati, OH | 634A Bronze | 0.019 m (3/4") |
| | Applicator Tip Assembly | | | |
| 24 | Kamlok adaptor | Dover Corp., OPW Division Cincinnati, OH | 633F Aluminum | 0.019 m (3/4") |
| 25 | PVC bushing | Ryan Herco, Burbank, CA | 3439-131 | 0.025 m NPT x 0.019 m NPT (1" NPT x 3/4" NPT) |
| 26 | Disc, rear | In-house fabrication | 6061 Al bar | 0.076 m (3") dia |
| 27 | Spacer rods | In-house fabrication | 6061 Al rod | 0.30 m (12") L, 3 required |
| 28 | Fabric clamp | Ryan Herco, Burbank, CA | 0950-052 | |
| 29 | a) Foam diverter | Local hardware store In-house fabrication | PVC pipe | 0.038 m dia x 0.076 m L (1½" dia x 3" L) |
| | b) Round head screws | Local hardware store | -- | 8-32, 0.006 m (¼") L, 2 required |
| | c) Nuts | Local hardware store | -- | 8-32, 2 required |
| | d) Plumber's tape | Local hardware store | -- | 0.019 m W x 0.051 m L (3/4" W x 2" L), 2 required |
| | e) Round head screws | Local hardware store | -- | 8-32, 0.013 m (½") L, 2 required |
| 30 | a) Connecting rods | In-house fabrication | 6061 Al bar | 0.25 m (9-3/4") L with 10 x 32 ends, 3 required |
| | b) Disc, front | In-house fabrication | 6061 Al bar | 0.038 m (1½") dia |
| | c) Rod nuts | Local hardware store | -- | 10-32, 3 required |
| 31 | a) Fabric | Stauffer Chem., Elmsford, NY In-house fabrication | VL9022FR on polyester cotton blend fabric N2F126B | 0.33 m W x 0.79 m L (13" W x 31" L), flat |
| | b) Vent slot | Stauffer Chem., Elmsford, NY In-house fabrication | VL9022FR on polyester cotton blend fabric N2F126B | 0.076 m W x 0.36 m L (3" W x 14" L), 2 required |
| | c) Tygon tube | Ryan Herco, Burbank, CA | -- | 0.0095 m OD x 0.23 m L (3/8" OD x 9" L), 2 required |
| 32 | Rubber band | Local hardware store | -- | 0.051 m (2") dia |

Note 1: Each unit of the prototype leak-plugging system also contains four AP50C-4 and one AP50C-6 copper conical seals, available from Airdrome, Long Beach, CA.

Note 2: The following working drawings of the external leak plugger have been produced: External Leak Plugger Assembly, EMSC Drawing No. 10000060; Foam Lance Assembly, EMSC Drawing No. 10000061; Gas Pressurant Assembly, EMSC Drawing No. 10000062; Applicator Tip Hardware Assembly, EMSC No. 10000063; and Applicator Tip Fabric Assembly, EMSC No. 10000064.

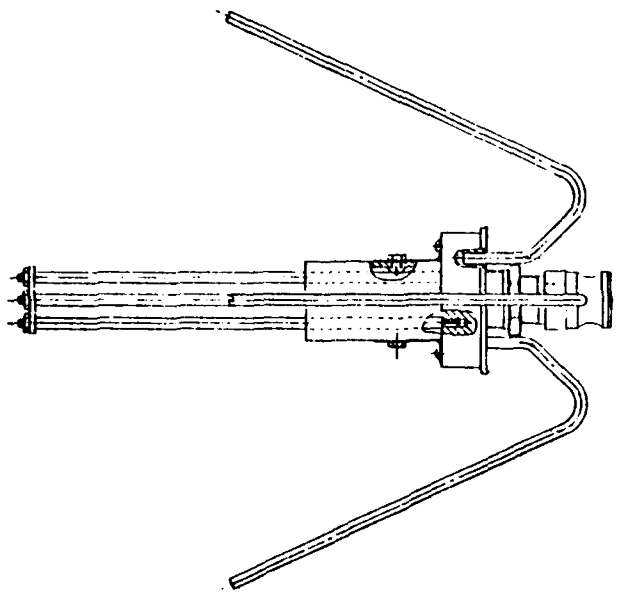

Figure 22. Applicator Tip Hardware Assembly

fabricated with two lengthwise slots for venting the expelling gases. Proper rigid foam plug formation dictates that the applicator tip be provided with adequate means for venting the solvent and blowing agent vapors present in the polystyrene mixture. To prevent the vent slot from being pinched closed as the hole is being sealed, a plastic tube is inserted in the vent slot pocket during fabrication. The fourth or open edge of the pocket is sealed with a temporary plug. This temporary vent plug consists of a non-curing putty, such as Dap rope caulk, and is used in underwater applications to prevent water from entering the vent slot before the device is used. When the polystyrene foam enters the device, the venting gases dislodge the temporary vent plug and expel at the rear of the applicator tip away from the hazardous chemical cargo, thereby reducing the opportunity for the hazardous chemical and the polystyrene to come in direct contact with each other. In addition, the fabric outer surface is coated with a polymeric material, such as Gacoflex Hypalon H-2220 or 3M Protective Coating 1706, to provide a fabric surface compatible with most hazardous chemical cargos.

For underwater applications, the external leak plugger is equipped with a buoyancy package, as seen in Fig. 20, so that the charged delivery system will be almost neutrally buoyant before use, and yet the spent lance will have a somewhat positive buoyancy. This enables the scuba diver to release the spent lance after detaching it from the foam plug, by means of the Kamlok connector, with the assurance that it will rise to the surface of the water where operational personnel can retrieve it for reuse. In addition, the buoyancy package is split into two sections so that its center of buoyancy will coincide with its center of gravity, thereby making it easier for a scuba diver to manipulate.

To prepare the device for firing, an applicator tip is attached to the front end of the lance by means of a Kamlok connector, and then a $CO_2$ gas cartridge is attached to the inflator in the gas pressurant assembly, thus arming the device. When the operator wishes to fire the system (after inserting the applicator tip into the hole to be sealed), he trips the T-bar firing mechanism puncturing the gas cartridge, thereby feeding carbon dioxide gas through a gas expansion tube into the rear of the lance. At this point the rear rupture disc breaks and the pressurant gas enters, driving a chrome steel ball against the pressurized foam mix. When the pressure again exceeds $2.17 \times 10^6$ pascals (300 psi), the front rupture disc gives way and the polystyrene foam exits the lance. Having previously been dissolved in liquefied compressed gases, the polystyrene comes out of solution as the compressed gases vaporize at the lower ambient pressures. At this time a polystyrene matrix forms, expanding and solidifying, resulting in a rigid foam plug. In addition, when the steel ball strikes the front burst disc assembly, it forms a seal, preventing the pressurant gas from entering the foam plug. The entire operation is completed in only a few seconds.

### 2.3.2 Prototype Testing

Since the new modifications were intended to improve ease of system operation, underwater tests of the prototype were conducted, accordingly,

in a private swimming pool to evaluate those modifications of the firing mechanism, foam buoyancy package, and applicator tip. The test results appear in Table 10. The firing procedure for the $CO_2$ gas cartridge, converted from the pulling of a lanyard to the squeezing of a T-bar/palm support, added mechanical stability to the firing mechanism and increased the reliability of the firing operation. The foam buoyancy package, split into two sections so that the center of buoyancy would coincide with the center of gravity, provided greater system maneuverability (see Figs. 23 and 24). These two modifications were definitely found, from the tests, to have enhanced delivery system performance.

The reason the foam plug results shown in Table 10 do not appear too promising is that an investigation was being conducted at the same time on a modification of the applicator tip and the modification did not meet expectations. To prevent the hazardous cargo material from contacting the

TABLE 10. UNDERWATER POOL TESTS OF PROTOTYPE LEAK-PLUGGING SYSTEM[a]

| Test Designation | Hole Shape/ Hole Size, m (in) | Plug Description | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, $kg/m^3$ ($lbm/ft^3$) |
|---|---|---|---|---|---|
| FT 1 | Circle/0.10 (4) | Good, large (far) and small (near) cylinders | 0.285 | 90 | 26 (1.6) |
| FT 2 | Triangle/0.15 (6) (on side) | Not good, rupture on seam | 0.321 | 92 | -- |
| FT 3 | Rectangle/ 0.10 x 0.13 (4 x 5) | Not good, rupture on seam | 0.320 | 92 | -- |
| FT4 | Rectangle/ 0.10 x 0.20 (4 x 8) | Not good, rupture | 0.324 | 91 | -- |

a - All tests were conducted in a private swimming pool by certified Rockwell divers. All test systems were loaded with a 2XF foam mixture, designated B1-2XF, and all applicator tips consisted of the usual hardware and vinyl upholstery fabric coated on the seams with PVC. All lances were equipped with a split buoyancy package of the following dimensions: 0.038-m (1½") thick x 0.2-m (8-inches) long (front); 0.038-m (1½") thick x 0.33-m (13-inches) long (rear). The buoyancy packages were made of Foamglas pipe insulation coated with Childers CP30. The water temperature during the tests averaged 301 K (82 F).

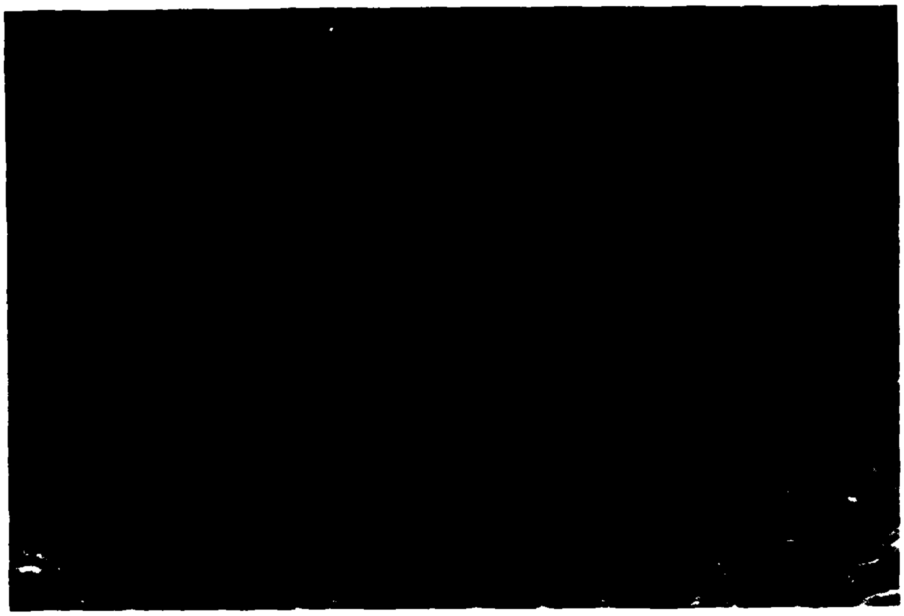

Figure 23. Prototype Leak-Plugging System Showing Split Buoyancy Package

Figure 24. Spent Prototype Lance Shown Floating on Water Surface

polystyrene within the foam plug, the seams of the tailored vinyl upholstry fabric were coated with PVC cement, leaving the fabric attachment point at the rear disc of the applicator tip as the only escape route for the outgassing vapors. When the outgassing vapors could not escape fast enough from around the rear disc, ruptures of the fabric occurred.

2.3.2.1 Laboratory Testing

A total of 26 experimental plugging tests using the prototype lances were conducted underwater in the laboratory. The parametric specifications and test results appear in Table 11. In every case, the prototype lances fulfilled their designated mission of foam containment and expulsion upon demand. The average expulsion efficiency was 91%, and the time for expulsion in every case was less than 3 seconds.

The last four underwater laboratory tests conducted at EMSC (LT23-LT26) evaluated the four new additional lances ordered by the Coast Guard. The tests also served to check out a new form of polystyrene polymer used for the first time in a foam formulation (see Section 2.4.3). The foam plugs formed from the new polystyrene formulation looked very good, both in size and shape. By every measure, the new lances, as well as the older ones, performed most satisfactorily.

Concurrently, within the same testing framework, the on-going study of applicator fabric design and fabric coatings was concluded satisfactorily. This effort completed an investigation begun earlier in response to a Coast Guard request to resolve the potential problem which exists when the expelling vapors are allowed to vent through the stitched seams in the applicator tip fabric, thereby providing a possible path for the hazardous cargo material to contact the polystyrene within the foam plug.

Three fabric designs were studied, and they had in common several features: they were all stitched with polyester thread, they were attached to the large aluminum applicator disc with a hose clamp, and they were

TABLE 11. UNDERWATER LABORATORY TESTS OF PROTOTYPE LANCES [a]

| Test Designation | Lance Designation | Applicator Tip Fabric Modifications | Fabric Coating[b] | Temp, °K (°F) | Circular Hole Size, m (in) | Plug Description | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, $kg/m^3$ ($lbm/ft^3$) |
|---|---|---|---|---|---|---|---|---|---|
| LT1 | A | Old; Seams, PVC | -- | 282 (48) | 0.10 (4) | Good | 0.329 | 90 | 35 (2.2) |
| LT2 | A | Old; Cap Seam, PVC; Slot | -- | 291 (64) | 0.13 (5) | Good | 0.320 | 92 | 30 (1.9) |
| LT3 | B | Old; Cap Seam, PVC; Flaps | -- | 291 (64) | 0.13 (5) | Not good, fabric hose clamp slipped | 0.317 | 92 | -- |
| LT4 | D | Old; Seams, PVC | -- | 292 (66) | 0.10 (4) | Good, exposed side seam | 0.251 | 88 | 26 (1.6) |
| LT5 | C | Old; Seams, PVC | -- | 292 (66) | 0.13 (5) | Very good, exposed side seam | 0.301 | 90 | 29 (1.8) |
| LT6 | C | Old; Cap Seam, PVC; Slot | -- | 293 (68) | 0.10 (4) | Good | 0.317 | 92 | 30 (1.9) |
| LT7 | D | Old; Cap Seam, PVC; Flaps | -- | 293 (68) | 0.10 (4) | Not good, ruptured on cap seam | 0.293 | 93 | -- |
| LT8 | B | Old; Seams, PVC | I | 293 (68) | 0.13 (5) | Not good, ruptured on cap seam | 0.285 | 91 | -- |
| LT9 | A | Old; Cap Seam, PVC; Slot | -- | 293 (68) | 0.10 x 0.20 (4 x 8) (Oval) | Good, exposed cap seam | 0.362 | 94 | 30 (1.9) |
| LT10 [c] | A | Old; Cap Seam, PVC; Slot | I | 294 (70) | 0.13 (5) | Good, exposed cap seam | 0.320 | 91 | 35 (2.2) |
| LT11 [c] | C | Old; Seams, PVC | II | 294 (70) | 0.10 (4) | Good, exposed cap seam and side seam | 0.271 | 93 | 34 (2.1) |
| LT12 | D | Old; Seams, PVC | III | 294 (70) | 0.10 (4) | Adequate, med. spheres | 0.251 | 89 | 35 (2.2) |
| LT13 | A | New | I | 293 (68) | 0.13 (5) | Very good | 0.320 | 90 | 29 (1.8) |
| LT14 | B | Old; Cap Seam, PVC; Slot | I | 293 (68) | 0.10 (4) | Good | 0.317 | 92 | 29 (1.8) |
| LT15 | C | New | I | 293 (68) | 0.10 (4) | Good | 0.318 | 90 | 30 (1.9) |
| LT16 | D | Old; Cap Seam, PVC; Slot | I | 293 (68) | 0.15 (6) | Good | 0.322 | 92 | 29 (1.8) |
| LT17 | B | New Rev. | I | 294 (70) | 0.10 (4) | Very good | 0.299 | 93 | 27 (1.7) |
| LT18 | A | New | I | 294 (70) | 0.10 (4) | Very good | 0.298 | 92 | 27 (1.7) |
| LT19 | B | New Rev. | I | 295 (72) | 0.10 (4) | Very good | 0.313 | 93 | 30 (1.9) |
| LT20 | C | New Rev. | III | 295 (72) | 0.10 (4) | Very good | 0.313 | 92 | 30 (1.9) |
| LT21 | A | New Rev. | III | 293 (68) | 0.13 (5) | Very good | 0.286 | 90 | 27 (1.7) |
| LT22 | D | New | I | 293 (68) | 0.15 (6) | Good | 0.258 | 90 | 22 (1.4) |
| LT23 | F | New Rev. | I | 293 (68) | 0.15 (6) | Very good | 0.320 | 93 | 27 (1.7) |
| LT24 | G | New Rev. | I | 293 (68) | 0.13 (5) | Very good | 0.314 | 91 | 27 (1.7) |
| LT25 | H | New Rev. | III | 293 (68) | 0.10 (4) | Very good | 0.309 | 90 | 26 (1.6) |
| LT26 | I | New Rev. | III | 293 (68) | 0.10 (4) | Very good | 0.309 | 90 | 29 (1.8) |

a - All tests were conducted in a laboratory water trough; tests LT1 - LT5 used formulation B1-2XF, tests LT6 - LT22 used formulation B2-2XF, and tests LT23 - LT26 used formulation A7-2XF.

b - The following coatings were available for application to the outside surface of the fabric: I, 3M Protective Coating 1706; II, Gacoflex Neoprene N-116; and III, Gacoflex Hypalon H-2220.

c - Duckbill polyester sailcloth fabric, rather than the usual vinyl upholstery fabric, was used for this test.

sealed to the disc with silicone rubber. The designs differed, however, as follows:

OLD - This design of applicator tip fabric used either vinyl upholstery fabric or duckbill polyester sailcloth fabric tailored to a 0.15-m (6-inch) diameter by a 0.30-m (12-inch) length, in a cylindrical shape with one lengthwise seam and a single end cap stitched to one end. In some cases, a strip of the same fabric was placed over the lengthwise stitched seam and sealed against the fabric on three edges with PVC cement. A Tygon tube was inserted within the pocket formed and the fourth edge, facing the hardware disc, was then sealed with silicone rubber. It was expected that this modification would provide the necessary venting of vapor at a suitable distance from the hazardous cargo within the ruptured tank hull.

NEW - This design used vinyl upholstery fabric tailored by folding the fabric over on itself, exposing the polyester cotton backing, and stitching on both sides, forming two lengthwise seams. Laid flat, the fabric appears as an isoceles trapazoid with a length of 0.38 m (15 inches) and a width that varies from 0.30 m (12 inches) at the folded end, to 0.19 m (7.5 inches) at the open end. The tailored fabric is then turned inside out, exposing the vinyl side, and a 0.36 x .08-m (14 x 3-inch) strip of the same fabric, vinyl side out, is laid over each seam and attached with PVC cement on three edges, forming a pocket over the seam with the open end near to,and facing, the large aluminum applicator disc. A 0.2-m (8-inch) length of 0.01-m (3/8-inch) OD x 0.0024-m (3/32-inch) ID Tygon tubing was inserted into the open end of each pocket which was then sealed with silicone rubber. This design not only provided the tailor with an easier stitching task, but also roughly doubled the rate of vapor expulsion when used, thereby reducing the stress on the fabric and resulting in faster and better plug formation.

NEW REVERSED - This design is similar to the "New" design except that the fabric was tailored with the vinyl side out and then turned inside out. Thus, the vent slots were attached with the polyester cotton backing

exposed. This technique was used when it was found that prohibitively long periods of time were required for curing the fabric coatings. By applying the coatings to the fabric backing, the curing times were considerably reduced.

Coating the stitched seams with PVC cement did not provide an adequate solution to the described problem, since in a sizable number of cases (LT4, LT5, and LT11) the cured PVC cement split upon plug expansion, producing good foam plugs but at the same time re-exposing the seams. In one case (LT8) the fabric, coated with 3M Protective Coating 1706 (a Neoprene-type polymer), actually ruptured at the cap seam. This clearly points out the critical nature of the venting operation; the plug must be provided with adequate means for venting the solvent and blowing agent vapors.

Once it was determined that a venting slot could be attached to the fabric and good plugs would result (LT2 and LT6), coatings were applied externally to the entire fabric, for ultimate compatibility reasons, and tested (LT14 and LT16) with similarly good results. Additional improvements to the concept were made leading to the "New" and "New Reversed" fabric designs which have produced excellent plug formations with a wide range of foam loadings. (See Table 11 and Figs. 25 through 28.)

The "New Reversed" fabric design applicator tip coated with Gacoflex Hypalon H-2220 or 3M Protective Coating 1706 is not only the best of the designs tested in the laboratory, but it is expected that it will prove to be a most satisfactory system in field use.

2.3.2.2 Field Testing

The large-scale foam loading system was disassembled, cleaned out, carefully packed, and air-freighted to the Coast Guard R&D Center for field trials in an ocean environment. At the same time, the prototype lances were cleaned out, new rupture discs installed, and the lances leak-checked. They were also shipped to the R&D Center, along with new lance buoyancy

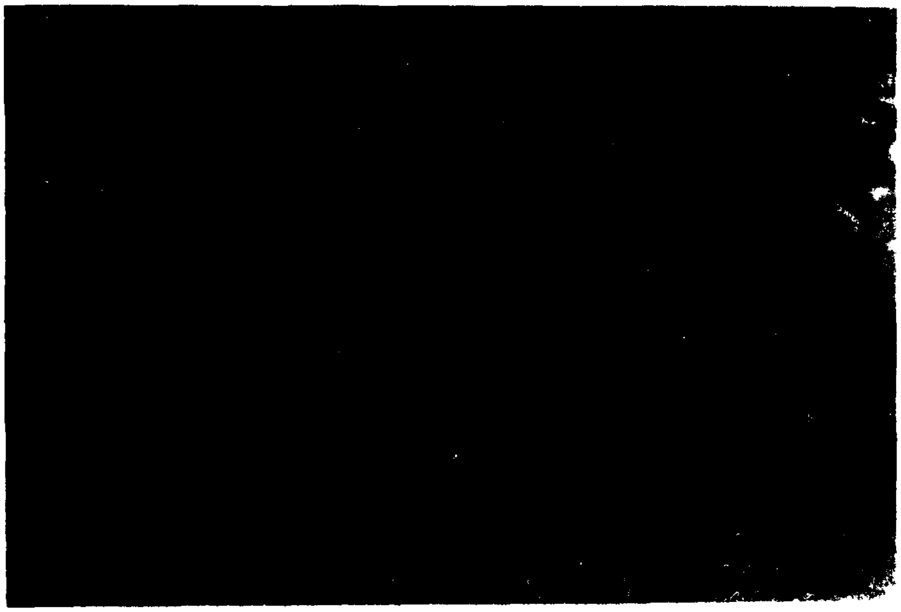

Figure 25. Test LT13 Plug, Using Fabric Design NEW Coated With 3M 1706, Shown in 0.13-Meter (5-Inch) Target Hole

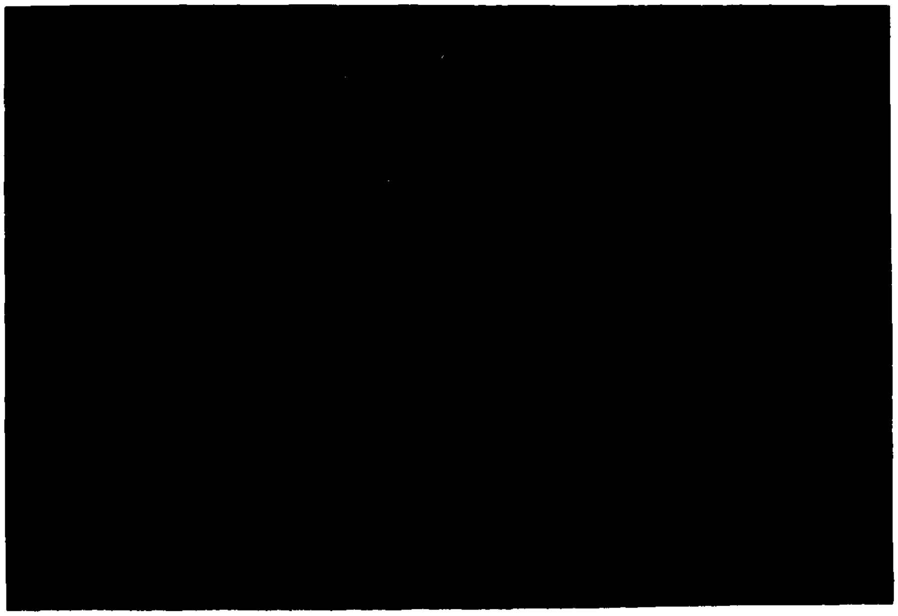

Figure 26. Test LT18 Plug, Using Fabric Design NEW Coated With 3M 1706, Shown in 0.10-Meter (4-Inch) Target Hole

Figure 27. Test LT19 Plug, Using Fabric Design NEW REVERSED Coated With 3M 1706, Shown in 0.10-Meter (4-Inch) Target Hole

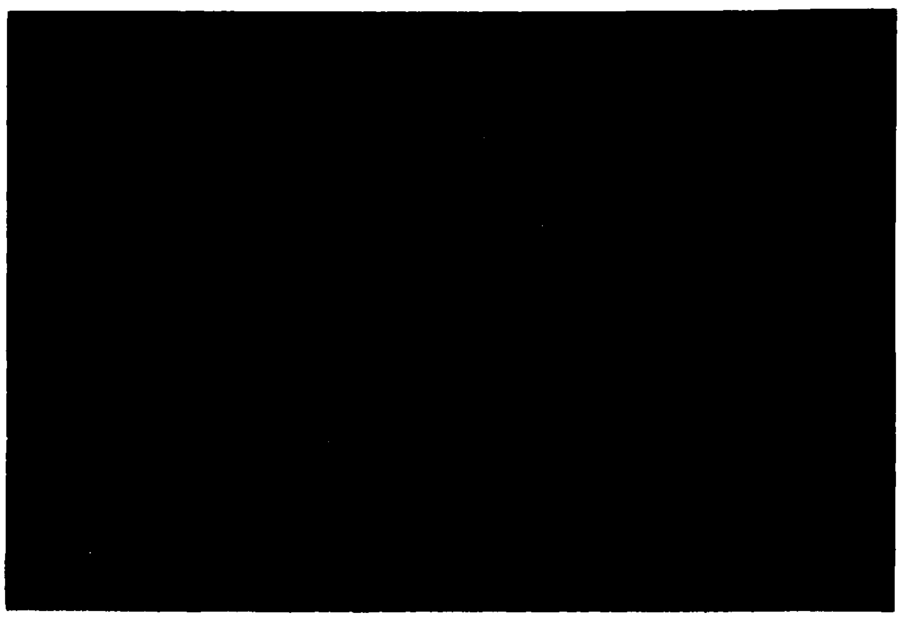

Figure 28. Test LT21 Plug, Using Fabric Design NEW REVERSED Coated With Gacoflex H-2220, Shown in 0.13-Meter (5-Inch) Target Hole

packages coated with 3M Protective Coating 1706, and 12 complete applicator tip assemblies of the "New Reversed" fabric design, double-coated externally, with the 3M coating on six units and Gacoflex Hypalon on the other six. In addition, four coated applicator fabrics, 36 rupture discs, 36 vacuum support discs, and 30 $CO_2$ cartridges were included.

The first order of business at the R&D Center, after uncrating, involved preparation of the polystyrene foam formulation. After experiencing the usual problems in mating compressed gas cylinders to their respective manual control valves, the connections were made and the compressed gases were added in the usual manner (see Section 2.4.2)

Fifteen individual tests of the prototype external leak plugger were conducted by the Coast Guard and the parametric specifications and test results are listed in Table 12. Foam pluggings were made at circular hole sizes of 0.05, 0.10, 0.15, and 0.20 m (2, 4, 6, and 8 inches), while target depths varied from 0.6 to 3.6 m (2 to 12 feet), on the average. Expulsion efficiencies averaged 90%, while the time for expulsion in every case was on the order of a few seconds.

Test runs from RDC9 to RDC15, which took place on August 17 before a contingent of Coast Guard officials, formed plugs that were, generally, very good (see Figs. 29 and 30). Preceding tests produced foam plugs that varied considerably in hole plugging effectiveness; some were good (RDC5 and RDC6), while others were only adequate (RDC1 and RDC2). Essentially all of the variation in quality of the earlier foam plugs was attributable to the temporary silicone rubber plugs on the applicator tip vent slots.

While it was recognized early that certain elements in the applicator tip fabrication, in particular the time allotted for curing of elastomers, would of necessity be increased from the original specifications if the applicator tips were to be prepared at EMSC prior to being shipped to the R&D Center, it was still imperative, in light of the testing schedule, that

TABLE 12. R&D CENTER UNDERWATER FIELD TESTS OF PROTOTYPE EXTERNAL LEAK PLUGGER [a]

| Test Designation | Lance Designation | Target Depth, m (ft) | Circular Hole Size, m (in) | Plug Description | Foam Wt, kg | Expulsion Efficiency, % | Plug Density, [b] $kg/m^3$ ($lbm/ft^3$) |
|---|---|---|---|---|---|---|---|
| RDC1 [c] | F | 3.7 (12) | 0.05 (2) | Adequate, but very small | 0.215 | 88 | -- |
| RDC2 | B | 3.7 (12) | 0.10 (4) | Adequate, but very small | 0.300 | 93 | -- |
| RDC3 | G | 3.7 (12) | 0.15 (6) | Satisfactory, but small | 0.290 | 91 | -- |
| RDC4 [d] | D | 3.7 (12) | -- | Misfired; large | 0.290 | 91 | -- |
| RDC5 | H | 3.7 (12) | 0.10 (4) | Good, medium size | 0.300 | 92 | -- |
| RDC6 | I | 3.7 (12) | 0.15 (6) | Good, medium size | 0.300 | 92 | -- |
| RDC7 | H | 2.4 (8) | SEE NOTE e | Satisfactory, but small | 0.350 | 94 | -- |
| RDC8 | C | 2.4 (8) | | Inadequate, very small | 0.340 | 82 | -- |
| RDC9 | A | 0.6 (2) | 0.10 (4) | Very good, large size | 0.330 | 89 | 29 (1.8) |
| RDC10 | D | 0.6 (2) | 0.15 (6) | Very good, large size | 0.350 | 89 | 18 (1.1) |
| RDC11 | F | 0.6 (2) | 0.05 (2) | Misfired, no expulsion | 0.290 | -- | -- |
| RDC12 | B | 0.6 (2) | 0.20 (8) | Good, very large size | 0.370 | 89 | 14 (0.9) |
| RDC13 | I | 3.7 (12) | 0.10 (4) | Very good, large size | 0.320 | 88 | 27 (1.7) |
| RDC14 | G | 3.7 (12) | 0.15 (6) | Very good, large size | 0.330 | 89 | 26 (1.6) |
| RDC15 [f] | F | 3.7 (12) | 0.05 (2) | Satisfactory; ruptured on near side | 0.290 | 88 | -- |

a - All tests were conducted by Coast Guard Strike Team divers, except for RDC1, from a flattop barge located near Pine Island in Fishers Island Sound off the Connecticut coast from Avery Point. The seawater temperature averaged 291 K (65 F) and all tests used foam formulation B3-2XF and the "New Reversed" applicator tip fabric design with the fabric double-coated with either Gacoflex Hypalon H-2220 or 3M Protective Coating 1706.

b - Measurements necessary for calculating plug density for several tests were not able to be obtained due to a "small craft warning" which brought the testing on one day to a rapid conclusion.

c - This test was performed by a certified Rockwell diver.

d - From all indications, the lance used in this test was apparently fired when the applicator tip was not in the target hole.

e - Used as fillers within large hole partially plugged with a large rubber bladder.

f - This test was a repeat test of lance F with a new $CO_2$ cartridge after the first test, RDC11, did not result in foam expulsion.

Figure 29. Tests RDC 9, 10, and 12 Plugs, Shown (From Top to Bottom) in Target

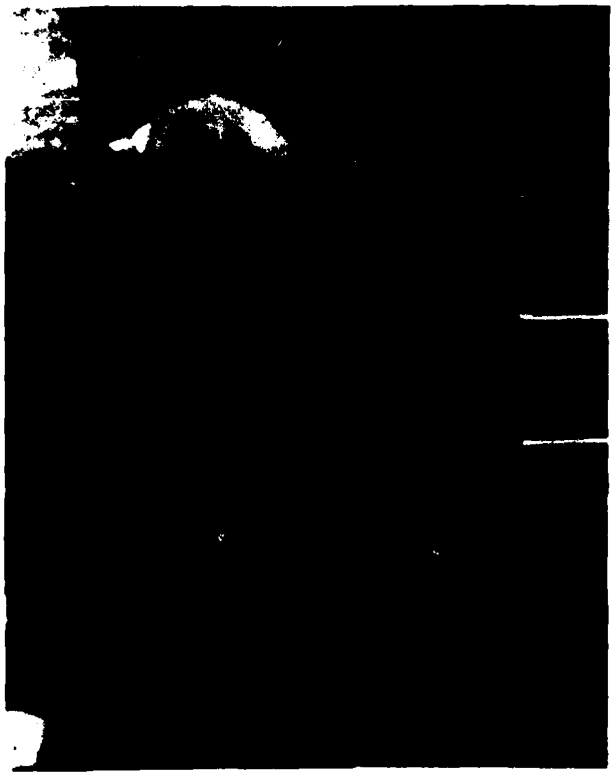

Figure 30. Tests RDC 15, 13, and 14 Plugs, Shown (From Top to Bottom) in Target

preparations such as the above take place at EMSC. However, it was felt that suitable measures could be taken to avoid any undesirable effects which might occur as a result of those changes. Since the critical nature of the foam plug venting operation was fully appreciated, the silicone rubber plugs on the applicator tips used in the RDC1-RDC6 test series were purposely slit by knife to facilitate proper gas venting. Upon conclusion of this test series, it was observed that the quality of the resultant foam plugs was not as good as had been the case in tests at EMSC. At the time, it was not fully recognized that the observed variations in foam plug characteristics were due to the silicone rubber since the tests involved several other changes in test parameters. It was not until the problem of inadequate plug formations was accentuated in two subsequent tests, RDC7 and RDC8, which used applicator tips in which the temporary silicone rubber plugs were punctured several times, rather than slit, that subsequent analysis of the situation uncovered the overcured silicone rubber as the primary reason for the problem.

Resolution of the problem was accomplished by stripping the temporary silicone rubber plugs from the remaining unused applicator tips and replacing them with freshly applied silicone rubber. In this way, subsequent tests, namely RDC9 through RDC15, used applicator tips which more closely duplicated those employed in laboratory tests at EMSC. The data from these tests, listed in Table 12, provide adequate confirmation of the accuracy of the conclusions reached. Not only were the foam plugs as good as those obtained at EMSC, but visual observations could detect no noticeable variation in plug size attributable to differences in depth over the range studied (see Figs. 29 and 30). A pliable putty, which does not set up or cure with time, such as Dap Rope Caulk, would seem a suitable replacement for silicone rubber as a temporary vent plug material.

#### 2.3.2.3 Shelf-Life Test

The work reported by Monsanto in Refs. 14 and 15 showed that long-term storage would not be a problem provided no leakage out of the foam lance is allowed to occur. Since the material in the tank is stored under

pressures of about 0.51 x $10^6$ to 1.48 x $10^6$ pascals (60 to 200 psi), depending on the foam formulation and its temperature, there is little chance that gaseous components from the air can enter into the tank. On the other hand, even a slight leakage from inside to outside would ruin the material inside the tank for use in leak plugging. Proper design can, however, provide a hermetic seal, making leakage very unlikely. In addition, sophisticated techniques can be used to check for minute leakages. Notwithstanding the above, a long-term storage surveillance program was started so that long-term storage capabilities would be evaluated as soon as possible.

A shelf-life test designed to provide information on the capability of the loaded foam lance to survive one-year storage periods without any loss in performance was begun. The lance is similar to prototype lances used in testing, and was loaded with 0.317 kg (0.70 lb) of B1-2XF foam in the usual manner. Thus far, after six months of storage, no loss in weight [measured to 0.0001 kg (2.2 x $10^{-4}$ lb)] has been detected.

## 2.4 LARGE-SCALE LOADING SYSTEM

A loading system for preparing and storing a substantial quantity of single-component foam for later transfer was designed, constructed, and tested.

### 2.4.1 Design

A conceptual sketch of the original large-scale loading system appears in Fig. 31, while Fig. 32 depicts a subsequent revision of the loading system. The loading system design includes the following features:

1. The system is capable of loading a number of individual leak-plugging lances from a single premixed formulation.
2. It includes a foam storage reservoir which is detachable from the rest of the system so that the foam ingredients, once introduced, can be mixed by suitable manipulation of the reservoir.

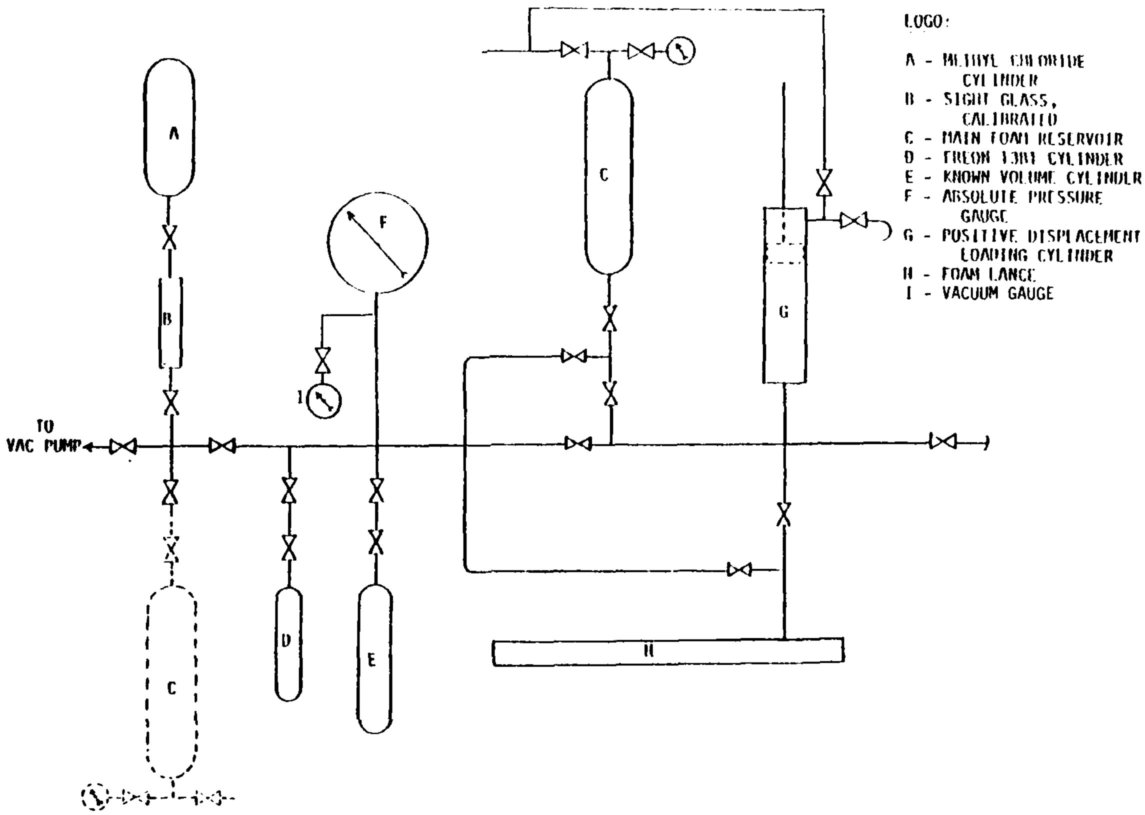


Figure 31. Schematic of Original Large-Scale Loading System

3. It is capable of handling pressures ranging from vacuum up to $1.48 \times 10^6$ pascals (200 psi).

4. It is capable of transferring measured quantities of compressed gases.

Key to the original system (Fig. 31) is the positive displacement loading cylinder (PDLC). It provides for loading a quantity of pressurized foam mixture into a lance while knowing the approximate amount of foam being loaded before disconnecting the lance from the loading system. Ultimate loading determinations are accomplished by accurate weighings using a balance. In addition, duplicate 0.0038-$m^3$ (1-gallon), high-pressure stainless steel cylinders (DOT-rated) were used in alternating roles as the main foam reservoir in the loading system, until they were replaced by

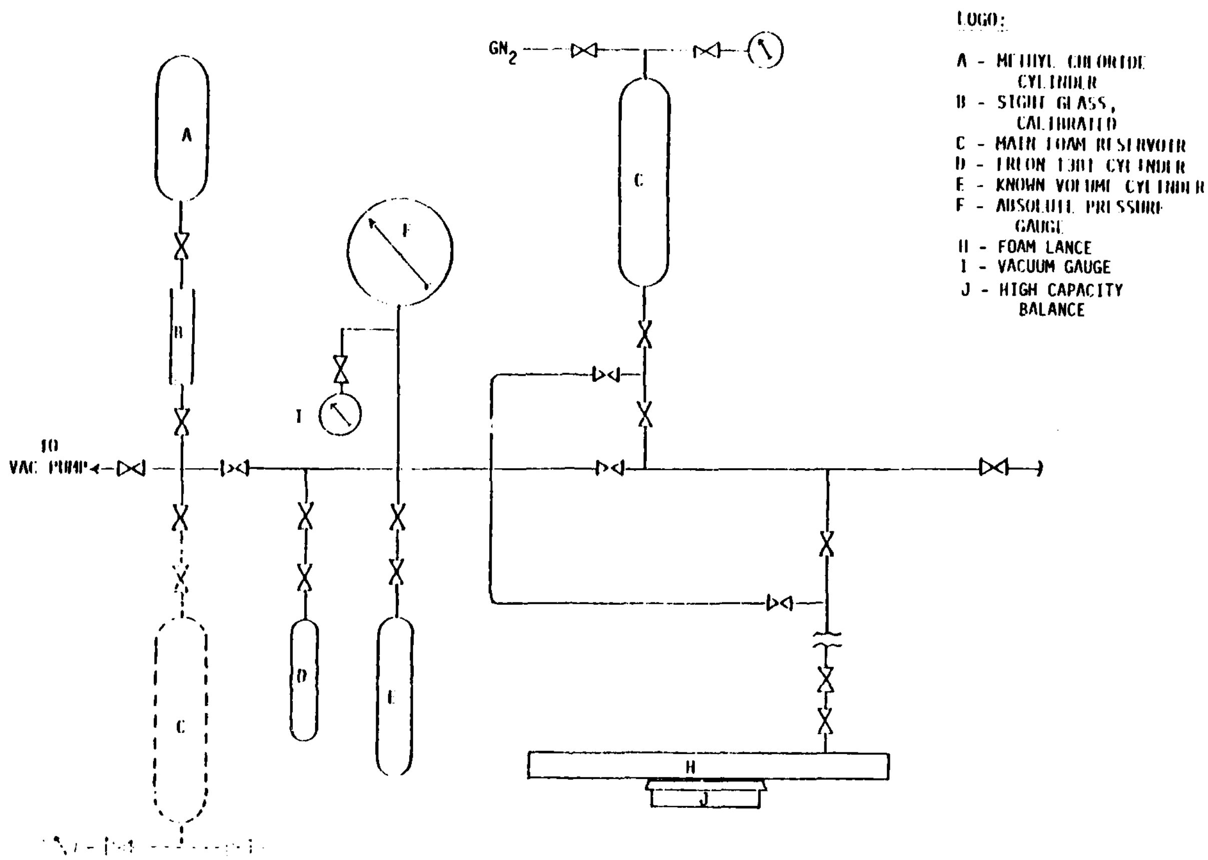


Figure 32. Schematic of Revised Large-Scale Loading System

a 0.0095-$m^3$ (2-1/2-gallon) cylinder. While the .0038-$m^3$ (1-gallon) cylinders could accommodate about eight lances per foam mix, the 0.0095-$m^3$ (2-1/2-gallon) cylinder could accommodate around 25 lances, thus providing a considerable savings in foam formulation time.

### 2.4.2 Operation

The large-scale loading system was constructed from stainless steel tubing and stainless steel AN fittings. Most valves were stainless steel although a few of the larger valves were brass. Upon completion of

leak-checking (by pressurization) of the large-scale loading system, shown in Fig. 31, selected line sections were volume-calibrated. This is typically done by isolating a quantity of gaseous nitrogen ($GN_2$), at a measured pressure in a known volume, such as E in Fig. 31, and then expanding the gas into selected portions of the loading system, which had previously been evacuated. After allowing for equilibration, the respective pressures obtained with each expansion are recorded and the selected volumes are then calculated from the Ideal Gas Law.

A polystyrene foam formulation is prepared by using the large-scale loading system and a double-ended, stainless steel cylinder (C in Fig. 31) attached on one end to a valve, for introduction of $GN_2$ (for transfer of foam), and a valved stainless steel pressure gauge. On the other end is a large valve (0.010-m [3/8-inch] orifice) which is removed when the polystyrene solids are being loaded and then is re-attached. A portion of the cylinder capacity is intentionally reserved for ullage volume, 20% for the 0.0038-$m^3$ (1-gallon) cylinders and 15% for the 0.0095-$m^3$ (2-1/2-gallon) cylinder.

The solids are pre-weighed and loaded into the tared, high-pressure cylinder, which has previously been leak-checked. The cylinder is then connected at position 1 (Fig. 31) to the loading system and evacuated slowly. When leak integrity is re-established, methyl chloride is added by gravity feed through the volume-calibrated sight glass. Chilling the cylinder is sometimes required. The cylinder is then removed from the loading system and the contents are allowed to mix at an elevated temperature [approximately 322 K (120 F)] for a few days. During the mixing period, the loaded cylinder is inverted lengthwise at least once every day to facilitate mixing. The viscosity of this material is so very high that when a container of it is inverted it takes a number of hours before the material flows into the new equilibrium position.

The cylinder is re-attached to the loading system at position 1 and loaded with Freon 13B1 by vacuum transfer. By measuring the pressure of Freon loaded within volume-calibrated portions of the loading system,

quantified amounts of Freon are added. Condensation of the Freon into the cylinder is accomplished by wrapping the cylinder with glass wool and chilling with liquid nitrogen ($LN_2$). The cylinder is subsequently removed and the contents allowed to mix, again at an elevated temperature, for a few days. During this time the cylinder is periodically inverted. After each loading of the compressed gases, $CH_3Cl$ and Freon 13B1, the cylinder is weighed to determine the exact amount of each gas added. (This could not be done in the case of the 0.0095-$m^3$ [2-1/2-gallon] cylinder since it had too high a tare weight for the capacity of the balance being used.)

To load the lances with foam mix, the main foam cylinder is attached, with the large valve at the bottom, to the loading system at position 2 (Fig. 31). A clean lance is attached to the loading system at the point indicated by the foam lance in Fig. 31. Foam is then transferred from C to G and thence from G to the lance using the procedure described in Table 13. This loading procedure was developed to assure (during transfer of the premixed foam) that the approximate amount of foam desired would be loaded into each lance. Ultimate determination of the foam quantity loaded is verified by weighing the lance, before and after loading.

The large-scale loading system was modified when a problem occurred while it was being used at the Coast Guard R&D Center. After using the system successfully to produce a foam formulation, gaseous nitrogen used as a pressurant began leaking across the piston seals of the PDLC, whereupon the loading operation was terminated, the lance unloaded, and the entire foam loading section of the large-scale loading system was disassembled and cleaned. When a second attempt to transfer foam according to the traditional procedure failed for apparently the same reason, consideration was given to an alternate loading procedure. (It should be noted that a similar experience had occurred once before when the loading system was in use at EMSC. After removing the 0.0038-$m^3$ [1-gallon] cylinder containing foam formulation A6-2XF and replacing it with the 0.0095-$m^3$ [2-1/2-gallon] cylinder containing B1-2XF, repeated attempts to use the PDLC to load foam into a lance failed. When diagnosis of the problem

TABLE 13. LANCE LOADING PROCEDURE

1. Tare lance and attach to large-scale foam-loading system.
2. Evacuate interconnecting volume and lance volume.
3. Verify vacuum integrity of lance and interconnecting plumbing.
4. Pressurize $GN_2$ system to $1.34 \times 10^6$ Pa (180 psig).
5. On positive displacement loading cylinder (PDLC), open and then close $GN_2$ valve ($GN_2$ vent is already closed), thereby pressurizing above piston to $1.34 \times 10^6$ Pa (180 psig). (Since piston is free to move, pressure below piston will also approach this value.)
6. Pressurize main foam reservoir (MFR) to $1.34 \times 10^6$ Pa (180 psig) by opening and then closing main $GN_2$ valve.
7. Open MFR fluid valves and leave open.
8. Barely open $GN_2$ vent valve for PDLC, allowing foam fluid to enter the PDLC slowly and the piston rod to rise slowly.
9. When rod is at full extension desired, close $GN_2$ vent valve and allow 15 minutes for adequate fluid transfer.
10. Introduce $CH_3Cl$ vapor ($0.59 \times 10^6$ Pa [70 psig] at 300 K [80 F]) to interconnecting volume and lance volume.
11. Close MFR fluid valves.
12. Open lance loading valve and open $GN_2$ valve to PDLC.
13. After piston rod completes its downward travel, wait 1 minute, then close lance loading valve.
14. Open $GN_2$ vent valve and slowly bleed $GN_2$ out until rod just starts to move up, then close $GN_2$ vent valve.
15. Remove lance by crimp-and-seal technique and, subsequently, clean solidified foam out of interconnecting fittings.
16. Weigh lance to determine net foam loading.

indicated the presence of a $GN_2$ leak across the piston, the loading cylinder was removed from the system and disassembled. Upon examination, it was found that solidified foam had worked its way across the piston U-cup seals, thereby causing the leak. A standby PDLC, similar to the first, was prepared and attached to the loading system and the problem was corrected.)

The modification ultimately employed (Fig. 32) had been utilized years earlier at the Rocketdyne Division of Rockwell International for transferring large quantities of low-viscosity rocket propellants, which had to be transferred in closed systems due to their pyrophoric nature. The procedure utilizes a large-capacity, accurate balance by which the lance to be loaded can be weighed while still connected to the large-scale loading system sans the PDLC. As $GN_2$ pressure (approximately $1.76 \times 10^6$ pascals [240 psi]) applied to the main foam storage cylinder at position 2 (Fig. 32) forces liquid foam into the lance, H, the increase in weight of the lance is monitored quite accurately by the balance, J. When the approximate desired weight of foam has been obtained, the proper valves are closed and the filling tube is crimped shut, completing the loading operation. With the tare weight of the lance and its final loaded weight known, a more accurate net weight can be obtained. The major drawback to the technique, as employed, was that it required long loading times, generally on the order of 1 to 1.5 hours per loading, in contrast to the 3/4 to 1-hour loadings with the original loading system. However, it is felt that major reductions in loading time could be obtained by redesigning the system based on this foam-loading concept.

It should be noted that experience showed the original large-scale foam-loading system was quite reliable and reproducible in controlling the amount of foam loaded when the procedure described in Table 13 was followed. When the procedure was modified to save time, the foam quantities loaded would vary from the values intended. Granted, of course, that the employed PDLC malfunctioned, the concept, nevertheless, should still be a viable one, given a practical and reliable PDLC.

### 2.4.3 Foam Formulation

Because of objections to two-component foams, in particular polyurethane, a survey was undertaken (Ref. 1) which resulted in a recommendation to use a single-component foam, polystyrene, in the leak-plugging system. The single-component polystyrene foam, developed by the Monsanto Corporation, has the following advantages: (1) wider temperature range, (2) simpler delivery system, and (3) reduced cost. As compared with other chemical foam systems, the temperature range of applicability is widened on the lower end, since the Monsanto work (Refs. 14 and 15) shows that successful expansion was obtained with this foam down to 263 K (14 F), a temperature well below the goal of 273 K (32 F) set for this effort. The delivery system is inherently simplified since only one component needs to be transferred to the applicator tip instead of two and the need for controlling mixture ratio is eliminated, increasing the potential for greater reliability. The cost is also lower since the number of components is reduced and manpower costs for assembly are proportionately less.

The foam is produced as follows: A powdered or pellet form of solid polystyrene is dissolved in a liquefied gas ($CH_3Cl$) while under relatively high pressure. When the pressure is released, at the point of use, the solvent instantly vaporizes, leaving behind the dissolved plastic which precipitates as thin, solid membranes surrounding the evaporated solvent. A matrix of small bubbles is formed having solid polystyrene walls and containing solvent vapor. A pneumatogen or blowing agent, Freon 13B1, is added to increase foaming at low temperatures, because of its low boiling point of 215 K (-72 F). It also imparts nonburning characteristics to the gas mixture (Ref. 14). Minor additions of other materials are made to the solution to aid in nucleation and lubrication. Glass microballoons serve as condensation nuclei for the formation of the small bubbles ultimately seen as the fine structure in the foam produced, and Igepal, a surface active agent, serves to enhance foaming and act as a lubricant so that the material flows through valves and tubing more easily. A more detailed description of the mechanism for the production of these foams can be obtained from Refs. 14 and 15.

The foam produced by this method is white and has a slightly springy feel to it, and is rather chemically inert. Development work utilizing this foam is aided by the fact that cleanup after experimentation is easily performed. Leftover material can be mechanically pushed from the inside of a smooth tube, resulting in a surface finish which is almost completely clean. Thus, foam tanks which had previously been used in an experiment could be refilled in minutes by merely pushing out the foam material remaining on the walls of the container. This is in sharp contrast to systems containing polyurethane in which lengthy procedures are required utilizing powerful solvents in order to clean components which have been exposed to the isocyanate.

The density of the single-component foams are comparable to those of the dual-component foam, running anywhere from around 16 $kg/m^3$ (1 $lbm/ft^3$) and higher, depending upon the conditions under which the foam is produced. Also, it has been demonstrated that the foam-producing mechanism is effective at an ambient pressure corresponding to a depth of about 15 m (50 feet) of water (Ref. 1) and temperatures ranging from 273 K (32 F) to ambient (see Section 2.2.3).

Two basic foam formulations were used during the program: A nominal (N) mixture and a double Freon (2XF) mixture with the latter exhibiting better low-temperature characteristics due to its use of twice as much Freon. The theoretical weight percentage compositions are as follows:

| Ingredient | N Mixture | 2XF Mixture |
|---|---|---|
| Polystyrene | 57.01 | 52.98 |
| Glass Microballoons | 1.08 | 1.00 |
| Igepal CO970 | 3.69 | 3.43 |
| Methyl Chloride | 30.62 | 28.46 |
| Freon 13B1 | 7.60 | 14.13 |
| | 100.00 | 100.00 |

The foam forumulations used experimentally and their compositions and mixing parameters are listed in Table 14. Formulations prepared in $0.0038m^3$ (one-gallon) cylinders are designated A, while those in the $0.0095m^3$ (2-1/2-gallon) cylinder are designated B. The weight percentages for the solids were obtained from their individual weights before they were mixed and loaded into the respective cylinders. The compressed gas percentages were determined by weighings of the respective cylinders as the ingredients were added, except for the B1-2XF, B2-2XF, and A7-2XF mixtures. Because of the high tare weight of the $0.0095m^3$ (2-1/2-gallon) cylinder, accurate weighings of the gases for B1-2XF and B2-2xF were not possible. Instead,the loading techniques established and developed during the earlier $0.0038m^3$ (one-gallon) cylinder loadings, and verified as quite adequate (as evidenced by Table 14) were relied on totally for loading the proper quantities of compressed gases. Because of the availability of a high capacity balance provided by the Coast Guard for the foam loadings during the R&D Center field trials, weighings could be made for the first time during the loading of the $0.0095m^3$ (2-1/2-gallon) cylinder. Thus, the composition of the foam formulation, labeled B3-2XF, could be verified. With the appropriate weighings having been made, the composition of foam formulation B3-2XF was verified, thus confirming once again that the loading techniques for preparation of the foam mixture were still reliable and quite satisfactory. The weight of methyl chloride added was within 0.5% of the intended value, while the Freon 13B1 loaded was 1.5% more than desired. Compressed gas loadings for A7-2XF were not verified because in the rush to evaluate a new polystyrene polymer, the required tare weights were not obtained.

When stocks of the original polystyrene pellets used in all previous foam formulations were found nearly depleted, an order was placed with Monsanto Corporation to replenish the stocks with the same polystyrene polymer. However, Lustrex HH100, a "granular crystal" form of polystyrene, was substituted for the original Lustrex HH101, a pellet form of polystyrene containing a small amount (approximately .01%) of lubricant. The

TABLE 14. POLYSTYRENE FOAM FORMULATIONS

| Foam Formulation[a] | Polystyrene,[b] Wt % | Glass Microballoons, Wt % | Igepal CO 970, Wt % | $CH_3Cl$, Wt % | First Mixing Time/Temperature, Hrs/°K (°F) | Freon 13B1, Wt % | Second Mixing Time/Temperature, Hrs/°K (°F) |
|---|---|---|---|---|---|---|---|
| A1-N | 55.0 | 1.0 | 3.6 | 31.6 | 98/297 (75) | 8.8 | 92/297 (75) |
| A2-2XF | 52.1 | 1.0 | 3.4 | 28.1 | 267/297 (75) | 15.4 | 215/297 (75) |
| A3-N | 57.3 | 1.1 | 3.7 | 30.6 | 97/297 (75) | 7.3 | 44/297 (75) |
| A4-2XF | 53.3 | 1.0 | 3.4 | 28.0 | 24/297 (75), 24/322 (120) | 14.3 | 121/322 (120) |
| A5-2XF | 53.2 | 1.0 | 3.4 | 28.4 | 262/297 (75) | 14.0 | 97/322 (120) |
| A6-2XF | 53.0 | 1.0 | 3.4 | 28.5 | 115/322 (120) | 14.1 | 168/322 (120) |
| B1-2XF[c] | 53.0 | 1.0 | 3.4 | 28.5 | 70/322 (120) | 14.1 | 95/322 (120) |
| B2-2XF[c] | 53.0 | 1.0 | 3.4 | 28.5 | 76/322 (120) | 14.1 | 71/322 (120) |
| A7-2XF[c, d] | 53.0 | 1.0 | 3.4 | 28.5 | 30/322 (120) | 14.1 | 162/322 (120) |
| B3-2XF[d] | 52.8 | 1.0 | 3.4 | 28.5 | 48/322 (120) | 14.3 | 66/322 (120) |

a - The designations A and B refer to the following cylinder sizes: A, 0.0038-$m^3$ (1-gallon), and B, 0.0095-$m^3$ (2-1/2 gallon).

b - The polystyrene used was Lustrex HH101, except as noted.

c - The addition of compressed gases to this formulation was not verified by cylinder weighings.

d - The polystyrene used in this formulation was Lustrex HH100.

reason given for the substitution was that the HH100 polymer was the only polystyrene available on the West Coast. It was noted that its availability was extremely limited, apparently because of a pilot plant problem (induced in part by restricted crude oil supplies), which resulted in dramatically curtailed polystyrene shipments, even to regular customers. Upon seeking and receiving the manufacturer's assurance that the HH100 polymer should solubilize in methyl chloride at least as fast as the HH101 without any detrimental effect on foam plug development, the decision was made to proceed with preparation of a foam formulation, A7-2XF, based on the new polymer and to test it in the new prototype lances (see Section 2.3.2.1).

## 2.5 LARGE PLUG FEASIBILITY STUDY

A detailed analytical evaluation has been completed of the feasibility of plugging larger holes up to 0.30 meter (12 inches) in diameter with poly-

styrene foam, using a delivery system involving a lance and probe. Three candidate delivery systems, each employing a different lance diameter, were considered. The study results are presented in the following text.

### 2.5.1 Sizing Requirements

The optimum configuration of the scaled-up leak-plugging system was determined by separating the nominal system into its components and analyzing the individual requirements, with respect to each candidate system, systematically, proceeding from one major subsystem to another, throughout the entire system.

#### 2.5.1.1 Plug

To plug larger holes up to 0.30 meter (12 inches) in diameter, a plug in the shape of a cylinder 0.33 meter (13 inches) in diameter and 0.2 meter (8 inches) long inside the hole, and 0.33 meter (13 inches) in diameter and 0.2 meter (4 inches) long outside the hole would be a feasible plug configuration. The total volume of this plug is approximately $2.61 \times 10^{-2}\ m^3$ (1590 $in^3$).

The fabric design is patterned after the prototype lance fabric configuration described as "New Reversed" (see Section 2.3.2.1). Laid flat, the fabric is dimensioned 0.38 meter (15 inches) in length and 0.58 meter (22.5 inches) in width. The total volume enclosed by the expanded fabric is approximately $3.16 \times 10^{-2}\ m^3$ (1930 $in^3$). The fabric size design will accommodate the foam volume expansion ratios at low and ambient temperatures, assuming volume expansion ratios similar to those experienced with the present prototype lance. At low temperature, the ratio averages 18 to 1 and at ambient temperature it is roughly 22 to 1.

#### 2.5.1.2 Lance Volume and Weight

A 0.05-m OD x 1.0-m L x 0.0012-m W (2-inch OD x 40-inch L x 0.049-inch W) lance loaded to 85% capacity with a 90% expulsion efficiency would produce

adequate quantities of expanded foam, at both low and ambient temperatures, to plug a 0.30-m (12-inch) hole. The inside volume of the foam tank is $1.85 \times 10^{-3}$ $m^3$ (113 $in^3$). At an 85% volume loading, the utilized foam tank capacity would be $1.59 \times 10^{-3}$ $m^3$ (97 $in^3$). With a liquefied foam density at 293°K (68°F) of $1.1 \times 10^3$ $kg/m^3$ (70 $lbm/ft^3$), $1.59 \times 10^{-3}$ $m^3$ (97 $in^3$) of foam would equal 1.75 kg (3.85 lbs) in weight. This weight of foam per loading at a 90% expulsion efficiency would produce $3.13 \times 10^{-2}$ $m^3$ (1910 $in^3$) in volume of expanded foam at ambient temperature and $2.56 \times 10^{-2}$ $m^3$ 1560 $in^3$) in volume of expanded foam at low temperatures, sufficient to plug a 0.30-m (12-inch) hole.

Consider the volume of the foam tank remaining the same, i.e., $1.85 \times 10^{-3}$ $m^3$ (113 $in^3$) (as would be the requirement for all incidents involving a 0.30-m [12-inch] hole), and using a 0.038-m OD x 0.0012-m W (1.5-inch OD x 0.049-inch W) foam tank, the requisite length of the foam tank will be 1.9 meters (74 inches). On the other hand, a 0.06-m OD x 0.0012-m W (2.5-inch OD x 0.049-inch W) foam tank would require a length of 0.6 meter (25 inches). While the 0.038-m (1.5-inch) OD foam tank would produce a lance whose length would place tremendous burdens on shipment and handling, the extremely short length of the 0.06-m (2.5-inch) OD foam tank would place the diver in greater jeopardy (due to his closer proximity to the hole and the hazardous material) and places an almost unworkable constraint on the dimensions of the buoyancy package (see Section 2.5.1.4). The 0.05-m (2-inch) OD foam tank, on the other hand, appears to be a reasonable and workable alternative.

In order to consider the weight factor, the weights, and also volumes, of the potential leak-plugging systems were listed by component in Table 15. Although foam tank weights decrease, not unexpectedly, from the smallest diameter lance to the largest, total system weights actually increase, due mainly to the weights of the respective burst disc assemblies. The highest system weight of 15.65 kg (34.4 lbs) with the polystyrene foam included does not appear prohibitively high for one man to handle or carry in the air and, of course, would be no problem at all in its intended element, i.e., underwater.

TABLE 15. POTENTIAL LEAK-PLUGGING SYSTEMS - WEIGHT AND VOLUME DETAILS[a] (Sheet 1 of 2)

| Item No. | Item Name | 0.038-m (1¼") OD Lance Weight, kg | 0.038-m (1¼") OD Lance Approximate Volume, $m^3 \times 10^5$ | 0.051-m (2") OD Lance Weight, kg | 0.051-m (2") OD Lance Approximate Volume, $m^3 \times 10^5$ | 0.064-m (2½") OD Lance Weight, kg | 0.064-m (2½") OD Lance Approximate Volume, $m^3 \times 10^5$ |
|---|---|---|---|---|---|---|---|
| | <u>Gas Pressurant Assembly</u> | | | | | | |
| 1 | $CO_2$ Cartridge | 0.241 | 8.5 | 0.241 | 8.5 | 0.241 | 8.5 |
| 2 | Inflator | | | | | | |
| 3 | T-bar firing arm | | | | | | |
| | a) Inflator cap nut | ~0.160 | ~3.4 | ~0.160 | ~3.4 | ~0.160 | ~3.4 |
| | b) Inflator stem | | | | | | |
| | c) O-ring | | | | | | |
| | d) Union | | | | | | |
| 5 | Elbow, swivel, SS | 0.033 x 2 | 0.4 x 2 | 0.033 x 2 | 0.4 x 2 | 0.033 x 2 | 0.4 x 2 |
| 6 | a) $CO_2$ expansion tube | | | | | | |
| | b) Sleeves | 0.066 | 1.8 | 0.066 | 1.8 | 0.066 | 1.8 |
| | c) Coupling nut | | | | | | |
| | <u>Foam Lance Assembly</u> | | | | | | |
| 7 | Elbow, SS | 0.045 | 0.6 | 0.045 | 0.6 | 0.045 | 0.6 |
| 8 | Bushing, SS | ~0.150 | ~1.2 | ~0.170 | ~1.4 | ~0.300 | ~3.5 |
| 9 | a) Fike burst disc assembly | | | | | | |
| | b) Rupture disc | 0.911 x 2 | 13.5 x 2 | 1.819 x 2 | 29.4 x 2 | 2.410 x 2 | 62.6 x 2 |
| | c) Vacuum support disc | | | | | | |
| 10 | Magnet | 0.135 | 2.5 | 0.140 | 2.6 | 0.145 | 2.7 |
| 11 | Clamp | | | | | | |
| 12 | Ball[b], chrome steel | ~0.170 | (2.23) | ~0.440 | (5.66) | ~0.890 | (11.5) |
| 13 | Cable tie | -- | -- | -- | -- | -- | -- |
| 14 | a) Buoyancy package, rear | 0.702 | 444 | 1.018 | 644 | 1.273 | 806 |
| | b) Buoyancy package, front | | | | | | |
| 15 | Clamp | | | | | | |
| 16 | a) Horizontal tube | | | | | | |
| | b) Vertical tube | 0.080 | 1.0 | 0.095 | 1.0 | 0.110 | 1.0 |
| | c) Saddle | | | | | | |
| 17 | Cable tie | | | | | | |
| 18 | Foam tank, $1.2 \times 10^{-3}$ m (0.049-inch) W | 2.124 | 214 | 1.544 | 206 | 1.217 | 202 |
| 19 | Fitting | ~0.05 | ~0.8 | ~0.05 | ~0.8 | ~0.05 | ~0.8 |

a - The table includes some data which, of necessity, had to be estimated.

b - The respective volumes for the chrome steel ball are not included in the volume totals.

<u>Note</u>: For buoyancy package calculations, see Section 2.5.1.4.

TABLE 15. POTENTIAL LEAK-PLUGGING SYSTEMS - WEIGHT AND VOLUME DETAILS[a] (Sheet 2 of 2)

| Item No. | Item Name | 0.038-m (1½") OD Lance Weight, kg | 0.038-m (1½") OD Lance Approximate Volume, $m^3 \times 10^5$ | 0.051-m (2") OD Lance Weight, kg | 0.051-m (2") OD Lance Approximate Volume, $m^3 \times 10^5$ | 0.064-m (2½") OD Lance Weight, kg | 0.064-m (2½") OD Lance Approximate Volume, $m^3 \times 10^5$ |
|---|---|---|---|---|---|---|---|
| 20 | a) Filling tube | | | | | | |
| | b) Sleeves | ~0.15 | ~1.0 | ~0.15 | ~1.0 | ~0.15 | ~1.0 |
| | c) Coupling nut | | | | | | |
| 21 | Kamlok coupler (mod.) | 0.454 | 13.8 | 0.794 | 34.6 | 1.134 | 43.8 |
| 22 | Chain | 0.260 | 0.4 | 0.567 | 0.5 | 0.794 | 0.6 |
| 23 | Kamlok plug | | | | | | |
| | Applicator Tip Assembly | | | | | | |
| 24 | Kamlok adaptor | 0.182 | 6.2 | 0.272 | 13.8 | 0.454 | 26.6 |
| 25 | PVC bushing | ~0.100 | ~2.0 | ~0.120 | ~2.2 | ~0.250 | ~3.7 |
| 26 | Disc, rear | 1.06 | | 1.06 | | 1.06 | |
| 27 | Spacer rods | 0.080 | | 0.080 | | 0.080 | |
| 28 | Fabric clamp | 0.050 | | 0.050 | | 0.050 | |
| 29 | a) Foam diverter | 0.060 | | 0.060 | | 0.060 | |
| | b) Round head screws | 0.006 | | 0.006 | | 0.006 | |
| | c) Nuts | 0.005 | | 0.005 | | 0.005 | |
| | d) Plumber's tape | 0.016 | | 0.016 | | 0.016 | |
| | e) Round head screws | 0.006 | ~280.0 | 0.006 | ~280.0 | 0.006 | ~280.0 |
| 30 | a) Connecting rods | 0.063 | | 0.063 | | 0.063 | |
| | b) Disc, front | 0.035 | | 0.035 | | 0.035 | |
| | c) Rod nuts | 0.005 | | 0.005 | | 0.005 | |
| 31 | a) Fabric | | | | | | |
| | b) Vent slot | 0.350 | | 0.350 | | 0.350 | |
| | c) Tygon tube | | | | | | |
| 32 | Rubber band | | | | | | |
| | Approximated Totals (w/o buoyancy packages): | 8.000 | 565 | 10.290 | 618 | 12.630 | 706 |
| | Approximated totals (w/buoyancy packages): | 8.700 | 1009 | 11.310 | 1262 | 13.900 | 1512 |
| | Approximated weight totals (w/buoyancy packages and foam): | 10.450 | -- | 13.060 | -- | 15.650 | -- |

a - The table includes some data which, of necessity, had to be estimated.

Note: For buoyancy package calculations, see Section 2.5.1.4.

2.5.1.3 $CO_2$ Cartridge

Since volume differences among the 0.038-m (1.5-inch), 0.05-m (2-inch), and 0.06-m (2.5-inch) OD foam tanks are rather small, calculated pressures inside the tanks will be very similar. Using the 0.05-m (2-inch) OD tank as a nominal system, the following carbon dioxide pressures were determined (refer to Fig. 33):

$P_1$, the pressure in $V_1$, i.e., the volume from within the $CO_2$ cartridge to the rear burst disc assembly before rupture of the rear burst disc

$P_2$, the pressure in $V_2$, i.e., $V_1$ plus the ullage volume in the lance before expulsion,(ignoring foam vapor contribution)

$P_3$, the pressure in $V_3$, i.e., $V_1$ plus the volume in the lance just subsequent to expulsion

Given that the vapor pressure of $CO_2$ at 298°K (77°F) is $6.3 \times 10^6$ Pa (920 psia), and applying the ideal gas law (since a rough approximation is sufficient), one can calculate the amount of $CO_2$ required for $P_1$. If $V_1$ is $1.20 \times 10^{-4}$ $m^3$ (7.3 $in^3$) (volume within gas pressurant assembly and rear Fike burst disc assembly), then weight of $CO_2$ gas to reach the vapor phase is calculated to be 0.015 kg (0.033 lbs). Using similar calculations for the other pressures in the lance leads to the conclusion that a 0.06 kg (2 ounces) net weight $CO_2$ cartridge will be adequate for the large leak-plugging system. Detailed calculations using this weight of carbon dioxide and determining the pressure at different locations in the lance are as follows:

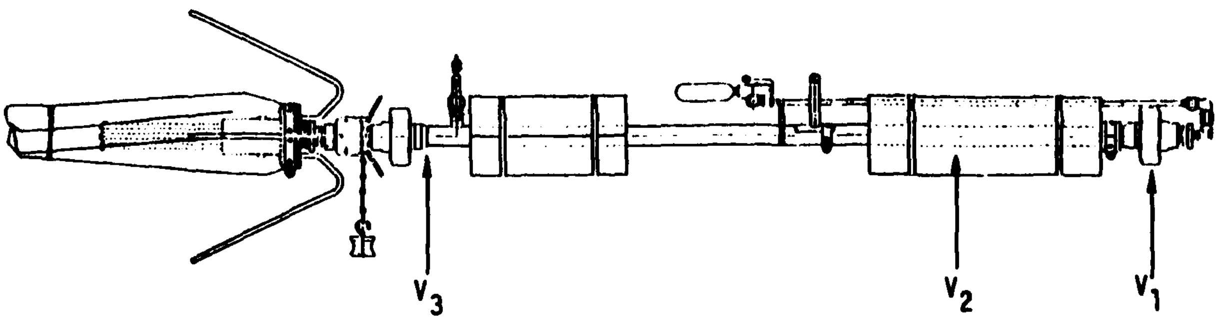


Figure 33. Nominal Leak-Plugging System Configuration

(a) At ambient temperature ($T = 298°K$ and $p_{CO_2} = 6.3 \times 10^6$ Pa),

$$P_1V_1 = n_1RT$$

$$P_1 \ (120) = 60/44 \times 82 \times 298$$

$$P_1 = 280 \text{ atm} = 2.8 \times 10^7 \text{ pascal or } 4100 \text{ psia}$$

The same calculation for $P_2$ and $P_3$ yields

$$P_2 = 80 \text{ atm} = 8.0 \times 10^6 \text{ pascal or } 1180 \text{ psia}$$

$$P_3 = 16 \text{ atm} = 1.6 \times 10^6 \text{ pascal or } 235 \text{ psia}$$

(b) At low temperature ($T = 273°K$ and $p_{CO_2} = 3.4 \times 10^6$ Pa),

$$P_1 = 250 \text{ atm} = 2.5 \times 10^7 \text{ pascal or } 3680 \text{ psia}$$

$$P_2 = 75 \text{ atm} = 7.5 \times 10^6 \text{ pascal or } 1100 \text{ psia}$$

$$P_3 = 15 \text{ atm} = 1.5 \times 10^6 \text{ pascal or } 220 \text{ psia}$$

Each calculated pressure exceeding the carbon dioxide vapor pressure at the given temperature indicates the presence of liquid $CO_2$. From these calculations, it appears that a 0.06-kg (2-ounce) net weight $CO_2$ cartridge will be adequate for a large plug, leak-plugging system.

#### 2.5.1.4 Buoyancy Package

The size of buoyancy package required for each of the selected candidate lances is listed in Table 16.

The buoyancy correction was determined by means of the equation for use of the system in salt water (see Section 2.2.1) and is, therefore, the minimum required. In actual practice, an increase in the required buoyancy package may be desirable as was the case with the developed prototype external leak plugger. This will accommodate the fresh-water application as well as provide sufficient buoyancy to float the spent lance within a reasonable period of time.

TABLE 16. MINIMUM BUOYANCY PACKAGES[a]

| Lance OD | 0.038-m (1-1/2") | 0.051-m (2") | 0.064-m (2-1/2") |
|---|---|---|---|
| Required Buoyancy Correction | $V_B = 4.4 \times 10^{-3}$ $m^3$ (270 $in^3$) | $V_B = 6.4 \times 10^{-3}$ $m^3$ (390 $in^3$) | $V_B = 8.1 \times 10^{-3}$ $m^3$ (490 $in^3$) |
| Minimum Amount of Buoyancy Material | 0.025-m (1") thickness of Foamglas Length: 0.86 m (34") | 0.038-m (1-1/2") thickness of Foamglas Length: 0.58 m (23") | 0.05-m (2") thickness of Foamglas Length: 0.43 m (17") |

a - Based on weight and volume estimates provided in Table 15.

Weights and volumes for each candidate lance were tabulated from the estimated values listed in Table 15. The average density of the Foamglas buoyancy package with 3M Protective Coating 1706 applied is 158 kg/$m^3$ (9.9 lbm/$ft^3$). The polystyrene foam weight is 1.75 kg (3.85 lbs).

A glance at Table 16 shows that the 0.06-m (2.5-inch) OD lance is the only system experiencing a physical constraint, assuming the final system has the general configuration depicted in Fig. 33. If allowance is made for the foam loading tube and the magnet, only 0.13 m (5 inches) of lance length remains unoccupied and, therefore, available for location of the $CO_2$ cartridge, T-bar firing mechanism, and the palm support, whereas in the prototype external leak plugger 0.30 m (12 inches) of length was provided for these items. A thicker buoyancy package is, also, not a solution since the present diameter of the 0.06-m (2.5-inch) OD lance with the smallest diameter buoyancy package possible is 0.165 m (6-1/2 inches) and already rather difficult to manipulate. Buoyancy packages for the other two lance candidates appear feasible.

### 2.5.1.5 Lance Wall Thickness

On the basis that the 0.05-m (2-inch) OD foam tank appears to be the most promising system, attention was focused on selected wall thicknesses for this tank size. The smallest wall thickness to be considered was

$1.2 \times 10^{-3}$ m (0.049 inch) since anything thinner would unduly risk wall damage. The working pressures for a selection of wall thicknesses were calculated. For straight metal pipe under internal pressure, the engineering equation for minimum required wall thickness $t_m$ is given (Ref. 16) for $D_o/t$ ratios greater than 4 as:

$$t_m = \frac{PD_o}{2(SE + PY)} + C$$

where

- $P$ = design pressure
- $D_o$ = outside diameter of pipe
- $C$ = sum of allowances for corrosion, erosion, and any thread or groove depth
- $S$ = allowable stress
- $E$ = longitudinal weld joint factor
- $Y$ = coefficient having a listed value for ductile ferrous materials, 0.4 for ductile nonferrous materials, and zero for brittle materials such as cast iron
- $t_m$ = minimum required thickness to which manufacturing tolerance must be added when specifying pipe thickness on purchase orders. (Most ASTM specifications to which mill pipe is normally obtained permit minimum wall to be 12-1/2% less than nominal.)

Simplifying by assuming seamless pipe ($E = 1$), no corrosion, erosion, or thread depth ($C = 0$), and no redistribution of circumferential stress ($Y = 0$), a conservative estimate, and solving for P gives:

$$P = \frac{2ST_m}{D_o}$$

For seamless stainless steel pipe at temperatures up to 366°K (200°F), a typical value of $1.293 \times 10^8$ Pa (18750 psi) for S (Ref. 16) was used in calculating working pressures for a variety of wall thicknesses of 0.05-m (2-inch) OD pipe and the results appear in Table 17.

TABLE 17. WORKING PRESSURES FOR 0.05-m (2-inch) PIPE

| Wall Thickness, m (in) | Working Pressure, Pa (psi) |
|---|---|
| $1.2 \times 10^{-3}$ (0.049) | $5.65 \times 10^{6}$ (805) |
| $1.5 \times 10^{-3}$ (0.058) | $6.65 \times 10^{6}$ (950) |
| $1.7 \times 10^{-3}$ (0.065) | $7.50 \times 10^{6}$ (1070) |
| $2.1 \times 10^{-3}$ (0.083) | $9.50 \times 10^{6}$ (1360) |

With a 2XF foam mixture vapor pressure at room temperature of approximately $6.9 \times 10^{5}$ pascals (100 psia) and at 328°K (130°F) of roughly $1.5 \times 10^{6}$ pascals (220 psia), any of the various wall thicknesses listed for a 0.05-m (2-inch) OD pipe in Table 17 appears quite adequate. Upon consideration of the maximum $CO_2$ pressure ($P_3 = 1.6 \times 10^{6}$ Pa) present in the pipe or tank subsequent to a room-temperature run (see Section 2.5.1.3), the various wall thicknesses again appear quite adequate. Also, even though the momentary $CO_2$ pressure ($P_2 = 8.0 \times 10^{6}$ Pa) within the lance before the front rupture disc breaks exceeds the calculated working pressure for several of the wall thicknesses listed in Table 17, there is no danger, since the burst pressure is approximately 4 times the working pressure and, in addition, the tank exposure to the $CO_2$ pressure is a very transient phenomenon. It is commonly accepted practice (Ref. 16) that pipe working pressures can be exceeded for brief periods without endangering personnel or equipment. It would appear, therefore, that pressure considerations are not significant enough to eliminate one or more of the selected wall thicknesses. However, weight is an important factor and, for this reason alone, the $1.2 \times 10^{-3}$-m (0.049-inch) wall thickness would be preferred over the other candidate wall thicknesses.

### 2.5.2 Loading Requirements

Using a $9.5 \times 10^{-3}$ $m^3$ (2-1/2-gallon) main foam reservoir and a given foam density of $1.1 \times 10^{3}$ $kg/m^3$ (70 $lbm/ft^3$) at 293°K (68°F) and saturation pressure, the total foam weight contained in a $9.5 \times 10^{-3}$ $m^3$ (2-1/2-gallon)

main foam reservoir loaded to 85% capacity wil be 8.85 kg (19.5 lbs). Then, using 1.75 kg (3.85 lbs) per loading, approximately five lances can be loaded for each foam formulation prepared in a $9.5 \times 10^{-3}$ $m^3$ (2-1/2-gallon) cylinder. For a 0.019-m (5-gallon) cylinder, approximately 10 lances can be loaded, and so forth, for larger system multiples.

Note: The tare weight of a typical $9.5 \times 10^{-3}$ $m^3$ (2-1/2-gallon) cylinder is 23 kg (50 lbs), while the tare weight of a 0.019-$m^3$ (5-gallon) cylinder is 41 kg (89 lbs). Unless other sources of pressurizable cylinders of less weight are found, the latter cylinder size is the largest size considered practical for manual manipulation.

Variation in polystyrene foam composition will likely change certain important physical properties of the foam formulation. These include density and viscosity and they, in turn, control the time required for mixing during foam formulation and, ultimately, could have a major impact on foam structure during expulsion. Unfortunately, only limited data on various polystyrene and other foam formulations are available; these were produced by Monsanto Corporation and appear in Ref. 14. Detailed characterization of the properties of foam formulations, in particular polystyrene foams, requires further experimental study. As a result of this shortage of property data for these foam formulations, some important aspects cannot be specified.

### 2.5.3 Environmental Considerations

It is especially important when considering environmental effects, where little hard data may exist, that comparisons between a scaled-up external leak plugger and the original prototype be used as much as possible. Thus, environmental factors such as buoyancy, water current, water (air) temperature, head pressure, working medium, and fauna were considered in light of any change which could be ascertained in their impact on a scaled-up system versus the prototype.

With respect to the diver, it is believed that a scaled-up system would present no more than a negligible effect over that of the original prototype.

Also, it should be noted that time is an important consideration in determining the role various factors can play, since the ability of the diver, lance, or plug to remain unaffected by various environmental factors will depend considerably on their length of exposure. Conclusions concerning the effects of various environmental parameters follow.

2.5.3.1 Buoyancy (Plug)

Forces acting on the submerged plug (both inside and outside the hull) are the plug gravity force, the fluid buoyancy force, and the fluid movement force. Determinations of the magnitude of the net forces acting on the submerged plugs, both with and without fluid movement, are shown in Table 18. The following equations were used to calculate the net forces:

$F_s = (\rho_f - \rho_p)gV$ and

$F_k = 6\pi\ \mu v_\infty R$

where:

$F_s$ = force associated with stationary fluid

$\rho_f$ = fluid density, $M/L^3$

$\rho_p$ = plug density, $M/L^3$

$g$ = gravitational acceleration, $L/t^2$

$V$ = volume of plug, $L^3$

$F_k$ = force associated with fluid movement

$\mu$ = fluid viscosity, $ML/t$

$v_\infty$ = approach velocity, $L/t$

$R$ = radius of plug, $L$

$\rho_f gV$ = buoyancy force

$\rho_p gV$ = gravity force

In the static case, there is a 350% increase in buoyancy of the scaled-up plug over the prototype plug, inside the hull, and a 450% increase outside the hull. In the dynamic cases, the net force increases of the

TABLE 18. NET FORCES ACTING ON SUBMERGED PLUG[a]

| Fluid Motion, m/sec (knot) | Prototype Plug: Forces Inside Hull, N (lbf), $\alpha^b$ | Prototype Plug: Forces Outside Hull, N (lbf), $\alpha^b$ | Scaled-Up Plug: Forces Inside Hull, N (lbf), $\alpha^b$ | Scaled-Up Plug: Forces Outside Hull, N (lbf), $\alpha^b$ |
|---|---|---|---|---|
| 0 | 29.8 (6.7), 90° | 13.1 (2.9), 90° | 133 (29.9), 90° | 71.5 (16.1), 90° |
| 0.51 (1) | --- | 13.1 (2.9), 86° | --- | 71.6 (16.1), 87° |
| 5.14 (10) | --- | 15.9 (3.6), 56° | --- | 81.0 (18.2), 62° |

a - The net forces were calculated using the following:

Prototype plug, nominal volume and weight of inside plug: $4 \times 10^{-3}$ $m^3$, 0.361 kg

nominal volume and weight of outside plug: $2 \times 10^{-3}$ $m^3$, 0.734 kg

Scaled-up plug, nominal volume and weight of inside plug: $1.7 \times 10^{-2}$ $m^3$, 1.220 kg

nominal volume and weight of outside plug: $8.7 \times 10^{-3}$ $m^3$, 1.700 kg

and fluid, nominal density: $0.85 \times 10^3$ kg/$m^3$ (53 lbm/$ft^3$)

nominal viscosity: 1.2 Pa·s (0.8 lbm/ft-sec)

b - $\alpha$ is the angle from horizontal of the net force vector.

scaled-up plug over the prototype plug are greater than 400%. Despite the relatively high percentage increases, it does appear, however, that the absolute values are not large enough to preclude development and use of a scaled-up leak-plugging system.

2.5.3.2 Water Current

<u>Lance</u> -- The profile of the scaled-up system will provide greater resistance to cross-currents and thus affect the diver's ability to introduce the applicator tip into the hole and to hold the lance in place while the

plug is solidifying. However, it is not believed that typical water currents will be strong enough to preclude the diver performing a successful plugging operation.

Plug -- As can be seen from Table 18, there is only a negligible change in the effect that 0.51 m/sec (1 knot) of water current, versus no fluid motion, has on either the scaled-up plug or the prototype plug, despite the greater cross-sectional area of the scaled-up plug (outside the hull). However, if the damaged vessel were to be moved to a new location for repairs, etc., at a nominal speed of 5.14 m/sec (10 knots), it would appear that the resultant increased water currents would have a greater absolute effect on the scaled-up plug than on the prototype plug (see Table 18); however, this greater effect is not considered significant enough to prohibit the use of the scaled-up leak-plugging system.

2.5.3.3 Water (Air) Temperature

Lance--Depending on the extent that a scaled-up lance is in thermal equilibrium with the water temperature at the time of use, the design configuration of the scaled-up lance could enhance or lessen the performance of the leak-plugging system. Since it has been shown, during the preprototype laboratory testing (Section 2.2.3.1), that expulsion efficiency is directly related to the rate at which the foam is expelled, a temperature change is expected to affect the system if it produces a change in the foam expulsion rate. However, in a system scaled-up by an increase in lance diameter, it is the designer's intent that expulsion times remain similar to those exhibited by the original prototype; thus, the volume flowrates will, of necessity, differ.

If both the scaled-up and original systems are at the same temperature and in thermal equilibrium with their surroundings when suddenly they are placed in surroundings at a different temperature, the original (smaller) system will reach thermal equilibrium with the new surroundings faster than the scaled-up system. This is due to the larger diameters of both the foam lance and the $CO_2$ cartridge used in the scaled-up system. Fur-

thermore, if the leak plugger is taken from storage at a warm temperature and plunged into cold water, the sooner the device is used the better its plugging performance will be. The scaled-up system will take more time to cool down to the water temperature and, thus, will perform more efficiently than the original (smaller) system during this period of transition. On the other hand, if the leak plugger is taken from storage at a cold temperature (as might be the case in winter if the device is stored on deck) and plunged into warm water, the scaled-up system will take more time to warm up to the water temperature and thus will perform less efficiently than the original system during this period of transition.

(Note: Although the $CO_2$ gas cartridges and net gas quantities for both scaled-up and original systems are dissimilar, since the gas cartridges were sized for the two different ullage volumes involved, the assumption has been made in the above treatment that the attainment of $CO_2$ vapor pressure, in both cases, after puncture of the gas cartridges is the same.).

Plug--As with the lance, various factors can influence the role that temperature will play in the formation of the scaled-up foam plug. Design of the scaled-up applicator tip, in particular, can accentuate or diminish such a role. For any size plug, the amount of fluid that is to be vaporized and, therefore, the amount of gas that is to be vented, depends on the volume of the foam plug and hence is proportional to the cube of the foam plug radius. The rate of fluid vaporization, however, depends on the fluid temperature and the rate at which the fluid can absorb heat from its surroundings, the latter being a surface-dependent phenomenon. Thus, the fluid vaporization rate is proportional to the square of the foam plug radius.

It can be seen from the above treatment that if two lances, namely, the scaled-up and the original, are at the same temperature when activated, the scaled-up foam plug will take more time solidifying than the original foam plug because of the greater cooling and resultant decrease in vaporization taking place in the scaled-up foam plug. However, alternate means

of increasing the rate of gas removal from the larger plugs should be considered. More and/or larger vent slots could be judiciously used to increase the fluid vaporization rate by lowering the gas pressure to counteract the effect of lower foam plug temperatures.

2.5.3.4 Head Pressure

Lance -- No effect, or change in effect, should be possible due to head pressure since the lance is a sealed, noncompressible system, which cannot detect head pressure until the front rupture disc breaks during the expulsion process.

Plug -- Only minor variations should occur between scaled-up and prototype plugs due to the effect of head pressure. Plug density is, of course, dependent on head pressure, but if foam expulsion times and efficiencies are similar, density differences between larger plugs and original-size plugs at a given head pressure should be negligible.

2.5.3.5 Working Medium

Lance -- Although exposure times are very limited, hardware components were chosen for their ability to resist corrosion in seawater, brackish water, and fresh water contaminated with hazardous chemicals. There is no reason to believe that a scaled-up system would be any less compatible with the medium than the prototype is.

Plug -- Similar materials of construction presumably would be used for the scaled-up system as with the prototype. Although any unit area would see the same exposure regardless of plug size, it is possible that if the scaled-up fabric has to be designed differently and the new design exposes different portions with varying degrees of compatibility (to hazardous chemicals) that a change could result which might be significant. However, this does not appear likely at this time. On the other hand, compatibility testing of the coated prototype fabric over varying lengths of exposure with selected hazardous chemicals has never been experimentally performed.

### 2.5.4 Conclusions

The large plug feasibility study has produced no serious technical objections to the concept of developing and using a scaled-up leak-plugging system. The study shows that no insurmountable engineering problems preclude its development. Investigation of the sizing requirements based on the 0.30-meter (12-inch) hole size found that a 0.05-m OD x 1.0-m L x 0.0012-m W lance (1) could provide adequate quantities of expanded foam, at both ambient and low temperatures, to plug the hole size of interest, (2) would be able to contain the pressures expected, (3) would not be prohibitively large or heavy for handling in air or manipulating underwater, (4) could be fabricated with a suitable $CO_2$ cartridge, and (5) could be assembled with an adequate buoyancy package to meet the design requirements. It has also been shown that other candidate systems, based on the same general configuration, lack one or more of these qualifications possessed by the selected system.

With the experience gained from the development of the prototype external leak plugger, realistic comparisons were able to be made between a scaled-up system and the original prototype in terms of the effect of selected environmental factors on each. If differences in the effects of these variables are identified as insignificant or, if otherwise, are determined not to be disadvantageous, then the scaled-up system has a predictably good chance of being successful. Thus, it was determined that (1) the buoyancy forces, inside and outside the hull, though significantly greater in the case of the scaled-up plug, are not of a magnitude that would pose a problem for the larger plug, which should be structurally sound enough to withstand them, (2) water currents, which also would exhibit a greater effect on the scaled-up plug, would not jeopardize the plug's integrity at the velocities cited, (3) temperatures will either have no effect on the performance of the scaled-up system versus the prototype, or will favor the scaled-up system if the applicator tip is optimized for the larger system, and (4) head pressure and working medium are not expected to have a significantly greater impact on the scaled-up system than they did on the prototype.

It is concluded, therefore, that the development of a scaled-up leak-plugging system has a high probability of success and can be actively pursued in order to extend the Coast Guard's hole-plugging capability to 0.30-meter (12-inch) holes and, thereby, provide further protection of the environment.

## 2.6 SYSTEM INTEGRATION

The objective of this task is to further the production and deployment of the external leak plugger as a viable tool of the Coast Guard in its effort to limit pollution spills. The objective was accomplished through four subtasks: Optimized Configuration Development, Scenario Analysis, DOT Rating, and Training Program.

### 2.6.1 Optimized Configuration Development

The prototype leak-plugging system was evaluated with respect to optimizing the system for shipping. Several shipping configurations were considered by, first, selecting several candidate configurations, second, determining system modifications required by the respective shipping configurations, third, listing the advantages and disadvantages recognized as inherent in each configuration, and fourth, analyzing all of the options to ascertain the optimum shipping configuration.

FIRST OPTION: Gas pressurant assembly, foam lance assembly, applicator tip assembly, buoyancy package, and $CO_2$ cartridge shipped individually.

1. Foam Lance Assembly
   - (a) The rear end of foam lance is capped with an AN cap on the elbow fitting.
   - (b) The other end of foam lance has a Kamlok plug to plug the Kamlok coupler.
2. Gas Pressurant Assembly. Protective tape is used to cover both ends of the assembly.
3. Applicator Tip Assembly
4. $CO_2$ cartridge (with small packet of thread lubricant)
5. Buoyancy package

Advantages of above configuration:

1. $CO_2$ cartridge is not on the system. Potential for a premature firing is reduced.

2. Only the loaded foam lance is considered for DOT exemption.

Disadvantages of above configuration:

1. Operator must remove protective tape from gas pressurant assembly.
2. Operator must lubricate $CO_2$ cartridge threads and then insert cartridge into inflator.
3. Operator must remove AN cap from foam lance, then attach gas pressurant assembly to the foam lance assembly.
4. Operator must attach buoyancy package to lance.
5. Operator must remove Kamlok plug and attach applicator tip assembly to lance.

SECOND OPTION: Gas pressurant assembly and foam lance assembly shipped together (without $CO_2$ cartridge in the inflator). Applicator tip assembly and $CO_2$ cartridge shipped separately.

1. Foam lance assembly and gas pressurant assembly attached; the inflator does not have a $CO_2$ cartridge installed.
   (a) The inflator is plugged at open end by using a steel flathead, hex socket screw.
   (b) The front end of foam lance has a Kamlok plug to plug the Kamlok coupler.
2. Applicator Tip Assembly
3. $CO_2$ cartridge (with small packet of thread lubricant)

Advantages of above configuration:

1. $CO_2$ cartridge is not on the system. Potential for a premature firing is reduced.
2. The gas pressurant assembly is attached to the foam lance assembly at the factory.
3. The buoyancy package is attached to the lance at the factory.

Disadvantages of above configuration:

1. Operator must remove the plug from the inflator.
2. Operator must lubricate the $CO_2$ cartridge threads and screw cartridge into inflator.
3. Operator must remove Kamlok plug and attach applicator tip assembly to lance.
4. The foam delivery system (lance and gas pressurant assembly) has to be considered for a DOT exemption.

THIRD OPTION: Gas pressurant assembly and foam lance assembly shipped together with $CO_2$ cartridge in the inflator. Applicator tip assembly shipped separately.

1. Gas pressurant assembly and foam lance assembly attached; the inflator has a $CO_2$ cartridge installed.
   (a) Inflator has an operator-removable safety clamp to hold the T-bar firing arm to prevent activation.
   (b) The front end of foam lance has a Kamlok plug to plug the Kamlok coupler.
2. Applicator tip assembly

Advantages of above configuration:

1. Operator only needs to attach applicator tip assembly to the lance assembly and remove the inflator safety clamp to prepare system for firing.
2. Although $CO_2$ cartridge is on system, the safety clamp has reduced the potential for a premature firing to a very low level.
3. Operator does not have to attach the cartridge to the inflator, considerably reducing the risk of cross-threading.
4. The gas pressurant assembly is attached to foam lance assembly at the factory.
5. The buoyancy package is attached to the lance at the factory.

Disadvantages of above configuration:

1. The clamp, a form of safety latch which holds the T-bar firing arm firm and secure, has to be removed by the operator.

2. $CO_2$ cartridge is on the system and must be included in consideration of modified foam delivery system for DOT exemption.

3. Operator must remove Kamlok plug and attach applicator tip assembly to lance.

FOURTH OPTION: The entire leak-plugger system shipped completely assembled; the inflator has $CO_2$ cartridge installed and a safety clamp to hold the T-bar firing arm to prevent activation.

Advantages of above configuration:

1. Operator only needs to remove the inflator safety clamp and the system is ready to fire.

2. Although $CO_2$ cartridge is on system, the safety clamp has reduced the potential for a premature firing to a very low level.

3. Operator does not need to assemble any portion of leak plugger.

4. Kamlok plug is no longer necessary.

Disadvantages of above configuration:

1. The safety clamp, which holds the T-bar firing arm firm and secure, has to be removed by the operator.

2. Entire external leak plugger must be considered for DOT exemption.

3. Requires a large container for shipping.

4. Without the Kamlok plug, the front rupture disc is more exposed to external puncture and if a rupture were to occur, besides rendering the lance useless, an applicator tip would also be expended.

The third option, i.e., the gas pressurant assembly and foam lance assembly shipped together with $CO_2$ cartridge in the inflator, was determined to be the optimum shipping configuration. While reducing the number of operations for the operator to almost a minimum, the third option provides an

adequate and necessary measure of protection for the foam delivery system by retaining the Kamlok plug. Also, it is easier to handle one, or perhaps even two smaller shipping containers required in the third option than the one large one required in the fourth option. The configuration described in the third option was, therefore, selected as the optimum and was described as the recommended shipping configuration in a DOT exemption application for shipping the loaded external leak plugger (see Section 2.6.3).

### 2.6.2 Scenario Analysis

To aid the Coast Guard in determining the most cost-effective approach for producing the external leak plugger in quantity, a manufacturing scenario analysis was undertaken. The following three scenarios (showing, also, the vendor who supplied the cost data) were analytically evaluated:

CASE 1: All fabrication, assembly, and loading/reloading - Rockwell EMSC

CASE 2: All fabrication and assembly - Conejo Industries Inc.
All loading/reloading - Rockwell EMSC

CASE 3: All hardware fabrication - Conejo Industries Inc.
All assembly including fabric and buoyancy packages - Rockwell EMSC
All loading/reloading - Rockwell EMSC

The cost benefit analysis was performed on each scenario based on the fabrication of 60 devices and a usage rate of 180 firings annually (Ref. 17).

To provide the necessary cost data, formal Request for Quotation (RFQ) packages for the three basic scenarios were assembled and delivered to the EMSC Purchasing Department for processing. The Purchasing Department contacted a group of explosives manufacturers who expressed interest in the work, and, as a result, the packages were forwarded to them for quotes. Unfortunately, not a single quote was forthcoming. The reason cited by the manufacturers was that, since the leak plugger is not explosively discharged and does not otherwise involve chemicals of an explosive nature, their higher costs would result in quotes which would be noncompetitive in

comparison with other manufacturers. Therefore, they chose not to bid. The manufacturers contacted were:

1. Gulf Oil Chemicals Co.
   (Explosives Dept.)
   Shawnee Mission, KA

2. Jet Research Center
   Arlington, TX

3. Technical Ordinance, Inc.
   St. Bonifacius (Minneapolis), MN

4. Whittaker Corp.
   (Bermite Division)
   Saugus, CA

A second set of RFQ packages was then sent to a combination of chemical manufacturers and machine shop vendors. As with the first group, their responses were also rather discouraging. Except for Conejo Industries Inc., a machine shop vendor, none of the remaining companies chose to bid because, as they noted, they lacked the knowledge, capability, or desire to handle the fluidized polystyrene foam. The companies in this second group contacted by the EMSC Purchasing Department were:

1. BSAF Wyandotte
   Wyandotte, MI

2. Conejo Industries Inc.
   Newbury Park, CA

3. Inflatable Systems
   Orange, CA

4. Monsanto Plastics & Resins Co.
   Newport Beach, CA

5. Soni-Form Inc.
   El Cajon, CA

6. Tuscarora Plastics
   New Brighton, PA

7. Voight Corp.
   Santa Ana, CA

8. Whittaker Corp.
   Minneapolis, MN

To facilitate development, therefore, of the scenario analysis, experience gained at EMSC during the course of the program was used to estimate the costs which might be incurred if all, or part, of the production and loading of the external leak plugger were to be performed by Rockwell at the EMSC facility. Thus it was that EMSC provided the cost data for Case 1, for which the estimated manhours and dollar costs per unit are extended and tabulated in Table 19, while EMSC and Conejo Industries shared the responsibility for Cases 2 and 3, for which the dollar costs and extensions can be found in Tables 20 and 21, respectively. Quotes provided by Conejo Industries are believed representative and reliable. Cost estimates provided by Rockwell for work at EMSC are for planning purposes only and are not to be construed as a bid nor as an intention to bid on the part of Rockwell. EMSC's labor costs were based on an average hourly rate of $30.

A comparison of the total costs for each scenario shows that the package offered in Case 2 is the lowest in cost, $77.4K, while Case 3 is a close runner-up at $83.5K. However, it is felt that Case 3 will ultimately prove to be the most cost effective due to reasons relating to quality control. It is very important for the proper fabrication and operation of the external leak plugger that quality control be maintained at high levels. This can best be served by using a vendor with the proper experience, i.e., one capable of independently inspecting machined parts (and rejecting those that are flawed) and assembling systems requiring leak-tightness under both vacuum and relatively high pressures. Thus, Case 3, the scenario involving all fabrication by one vendor, all assembly by another, and loading/reloading by, perhaps, a third is recommended for Coast Guard use.

TABLE 19. MANUFACTURING SCENARIO - CASE 1 [a]

| Unit | Manhours/ Unit | $/Unit | Total Manhours | Total ($K) |
|---|---|---|---|---|
| 1. Delivery System | | | | |
| Material [b] | -- | 325 | -- | 19.5 |
| Fabrication | 11.0 | 330 | 660 | 19.8 |
| Assembly | 2.5 | 75 | 150 | 4.5 |
| Subtotal | 13.5 | 730 | 810 | 43.8 |
| 2. Applicator Tip (Consumable) | | | | |
| Material | -- | 10 | -- | 1.8 |
| Fabrication | 3.0 | 90 | 540 | 16.2 |
| Assembly | 2.5 | 75 | 450 | 13.5 |
| Subtotal | 5.5 | 175 | 990 | 31.5 |
| 3. Foam Loading (L)/ Reloading [c] (R) | | | | |
| Material (L/R) | -- | 5/35 | -- | 0.3 + 4.2 |
| Formulation | 0.5 | 15 | 90 | 2.7 |
| Load/Reload | 2.5/4.0 | 75/120 | 150 + 480 | 4.5 + 14.4 |
| Subtotal (L/R) | 3.0/4.5 | 95/170 | 720 | 26.1 |
| Total (L/R) | 22/23.5 | 1000/1075 | 2520 | 101.4 |

a - This cost benefit analysis was based on the fabrication of 60 devices with a unit usage of three firings. The manhours and labor costs have been estimated for the work being done at Rockwell EMSC. Labor costs are based on an average rate of $30/hr. It should be understood that these estimates are for planning purposes only and do not constitute a bid nor do they indicate any intention of bidding on the part of Rockwell International. Also, all items are f.o.b. Newbury Park, CA. The foam loading/reloading estimates are predicated on (1) the large-scale foam loading system being transferred to EMSC from the Coast Guard R&D Center, and (2) a high-capacity balance being available for use. Total costs could increase approximately $6K for purchase of a new high-capacity balance and about $7K for a new loading system.

b - Includes the following consumables: rupture discs ($26), $CO_2$ cartridge ($1.50), and filling tube hardware ($3).

c - Reloading includes lance cleanup and assembly using the consumables listed in note "b".

TABLE 20. MANUFACTURING SCENARIO - CASE 2 [a]

| Unit | $/Unit | Total ($K) |
|---|---|---|
| 1. Delivery System | | |
| Material and Fabrication [b] | 512 | 30.7 |
| Assembly | 43 | 2.6 |
| Subtotal | 555 | 33.3 |
| 2. Applicator Tip (Consumable) | | |
| Material and Fabrication | 50 | 9.0 |
| Assembly | 50 | 9.0 |
| Subtotal | 100 | 18.0 |
| 3. Foam Loading (L)/Reloading [c] (R) | | |
| Material (L/R) | 5/35 | 0.3 + 4.2 |
| Formulation | 15 | 2.7 |
| Load/Reload | 75/120 | 4.5 + 14.4 |
| Subtotal | 95/170 | 26.1 |
| Total | 750/825 | 77.4 |

a - This cost benefit analysis was based on the fabrication of 60 devices with a unit usage of three firings. Delivery system and applicator tip costs were provided by Conejo Industries, Newbury Park, CA, while foam loading/reloading costs were calculated based on estimates provided by Rockwell EMSC, Newbury Park, CA. These estimates are for planning purposes only, and do not constitute a bid nor do they indicate any intention of bidding on the part of Rockwell International. Also, all items are f.o.b. Newbury Park, CA. The foam loading/reloading estimates are predicated on (1) the large-scale foam loading system being transferred to EMSC from the Coast Guard R&D Center, and (2) a high-capacity blance being available for use. Total costs could increase approximately $6K for purchase of a new high-capacity balance, and about $7K for a new loading system.

b - Includes the following consumables: rupture discs ($26), $CO_2$ cartridge ($1.50), and filling tube ($5).

c - Reloading includes lance cleanup and assembly using the consumables listed in note "b".

TABLE 21. MANUFACTURING SCENARIO - CASE 3[a]

| Unit | $/Unit | Total ($K) |
|---|---|---|
| 1. Hardware Fabrication | | |
| Delivery System | 507 | 30.4 |
| Applicator Tip | 45 | 8.1 |
| Filling Tube | 5 | 0.9 |
| Subtotal | 557 | 39.4 |
| 2. System Assembly | | |
| Delivery System (including buoyancy packages) | 75 | 4.5 |
| Applicator Tip (including fabric) | 75 | 13.5 |
| Subtotal | 150 | 18.0 |
| 3. Foam Loading (L)/Reloading[b] (R) | | |
| Material (L/R) | 5/35 | 0.3 + 4.2 |
| Formulation | 15 | 2.7 |
| Load/Reload | 75/120 | 4.5 + 14.4 |
| Subtotal (L/R) | 95/170 | 26.1 |
| Total | 802/877 | 83.5 |

a - This cost benefit analysis was based on the fabrication of 60 devices with a unit usage of three firings. Hardware fabrication costs were provided by Conejo Industries, Newbury Park, CA, while system assembly and foam loading/reloading costs were calculated based on estimates provided by Rockwell EMSC, Newbury Park, CA. These estimates are for planning purposes only, and do not constitute a bid nor do they indicate any intention of bidding on the part of Rockwell International. Also, all items are f.o.b. Newbury Park, CA. The foam loading/reloading estimates are predicated on (1) the large-scale foam loading system being transferred to EMSC from the Coast Guard R&D Center, and (2) a high-capacity balance being available for use. Total costs could increase approximately $6K for purchase of a new high-capacity balance and about $7K for a new loading system.

b - Reloading includes lance cleanup and assembly using the following consumables: rupture discs ($26), $CO_2$ cartridge ($1.50), and filling tube ($5).

AD-A088 104 ROCKWELL INTERNATIONAL NEWBURY PARK CA ENVIRONMENTAL--ETC F/G 11/1
FOAM PLUG DEVELOPMENT.(U)
DEC 79 R W MELVOLD, W TU, G H SMITH DOT-CG-81-78-1817
UNCLASSIFIED EMSC8316.1FR USCG-D-30-80 NL

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### 2.6.3 DOT Rating

The Department of Transportation was contacted concerning a DOT rating or exemption for shipping the foam-loaded lance. The proposed shipping configuration of the external leak plugger consisted of the foam lance assembly attached to the gas pressurant assembly with a safety-clamped $CO_2$ cartridge in the inflator. This is the option recommended as a result of the Optimized Configuration Development (see Section 2.6.1).

Indications were that an exemption could be obtained in approximately 120 days, while a DOT rating would possibly take up to a year (and the latter, with the probability that additional testing would be required). Therefore, an exemption was actively pursued and an application package was assembled for submittal.

The exemption application was formulated in accordance with CFR 49 §107.103 and the formal document was forwarded to the ESG Traffic Administrator, who, in mid-November, filed the request, in triplicate, with the Office of Hazardous Materials Regulation, Exemptions Branch, U.S. Department of Transportation. The application document is included as Appendix B. The U.S. Coast Guard and Rockwell International are listed as co-applicants and the proposed duration sought for the exemption is the maximum allowable, i.e., two years from date of issuance. Also, a request to have the application processed on a priority basis was made.

Included with the exemption application were copies of three external leak plugger working drawings, EMSC Nos. 10000060, 10000061, and 10000062, and an abridged version of the report by Sun et al (Ref. 14).

It is expected that suitable crating for shipments of the foam-loaded systems would involve the usual "strong wooden or fibreboard box" typically referred to in DOT regulations. At the same time, however, a little foresight indicates that this question may likely be resolved by the DOT within the framework of the exemption to be granted. As a result, this effort has been completed to the fullest extent possible pending a DOT ruling on the exemption application.

### 2.6.4 Training Program

To satisfactorily deploy the external leak plugger, the Coast Guard will find it necessary to train Strike Team divers in the proper use and operation of the device. To aid the Coast Guard in this assignment, a training program has been developed. The training program consists of a one-hour classroom session with the agenda shown in Table 22.

TABLE 22. TRAINING PROGRAM AGENDA

| Topic | Time, Mins. |
|---|---|
| Training program format sheet | 4 |
| Training film | 11 |
| Slide presentation - tape cassette and slide carrousel | 20 |
| Device sketch and instruction sheet | 5 |
| Question and answer forum | 10 |
| Inert leak plugger | 10 |
| Total | 60 |

The training program format sheet lists the training program, its objectives and selected instructional aids that will be provided to the trainees. The sheet is depicted as Fig. 34.

The training film shows the leak plugger, its basic components, the loading operation, testing of the device in the laboratory, and the firing of a lance underwater by a certified scuba diver. The film is designed to familiarize the viewer with the system. Appendix C contains film narration.

The slide presentation consists of a tape cassette dedicated to a slide carrousel which is capable of advancing the slides semi-automatically. The slide presentation is the core of the training program with its content directed toward the technical aspects and details of the system and its operation. Its purpose is to provide the trainee with the basic knowledge

Lesson: The External Leak Plugger and How to Use it

Type: Film, Narrated Slides, Q&A Session

Time: One hour

Objectives:

1. Provide brief background and basic concept
2. Describe the leak plugger in detail
3. Explain the operation of the leak plugger
4. Describe the research testing in general
5. Point out important improvements in the leak plugger
6. Provide a list of operational instructions
7. Discuss the device with the trainees – question and answer forum
8. Provide trainees with the opportunity to handle an inert leak plugger

Instructional Aids:

1. Film
2. Slides and tape cassette
3. Handouts:
    a. Training program format
    b. Sketch of the device
    c. Instruction sheet
4. External leak plugger (inert)

Figure 34. External Leak Plugger Training Program

necessary for properly using the external leak plugger. To do this effectively, the 10 basic steps for the satisfactory operation of the external leak plugger are reviewed, in detail, during the course of the narration.

The decision to use a slide narration as the core of the lecture is based on the premise that once the desired presentation is set, it should not change nor be dependent, but only indirectly, on the physical and emotional demeanor of the presenter. Therefore, the chance of misstatements or omissions is essentially eliminated. Also, the use of slides to complement the lecture should facilitate the trainee's understanding of the lecture material. The slide narration is contained in Appendix D.

In addition, a sketch of the external leak plugger, with appropriate captions describing important features of the device, and an instruction sheet, with the 10 basic operational steps, will be handed out to the trainees. The handouts are contained in Appendix E, which also includes the training program format sheet.

A question and answer forum will be provided so the trainees may have their questions answered and, at the same time, feel encouraged to participate in a group discussion concerning the device. An inert leak plugger is included as an instructional aid in the program so that each trainee will have the opportunity to see the actual device and familiarize himself with its handling characteristics.

Provision for a field practice session as part of the training program is considered optional, to be conducted at the discretion of the Coast Guard, since a substantial amount of time and money would be required to implement it.

## 2.7 TRAINING COAST GUARD PROJECT PERSONNEL

The training of Coast Guard project personnel was successfully completed. At the Coast Guard R&D Center, a Rockwell representative demonstrated (1) the use of the large-scale loading system in loading foam lances, (2) the proper procedures for assembling and leak-checking the lances, (3) the cleanout procedures for the lances and the main foam reservoir, (4) the formulation of new foam, (5) the fabrication of applicator tips and filling tubes, and (6) the firing of the external leak plugger. In addition, improvements were made to the large-scale loading system to facilitate the lance loading operation, and a successful firing of the external leak plugger in air was performed by the project officer.

## 3. CONCLUSIONS AND RECOMMENDATIONS

An effort has been conducted at the Environmental Monitoring & Services Center (EMSC) of Rockwell International in which improvements were made to an existing leak-plugging system designed for plugging underwater holes up to 0.1 m (4 inches) in diameter.

After earlier exploratory research determined that a single-component foam-generating technique would be applicable, an experimental system was developed that demonstrated the concept feasibility. The current program, sponsored by the U.S. Coast Guard Research & Development Center, witnessed the design, fabrication, and testing of an advanced leak plugger based on the experimental system. Thus, the device was converted from a multi-step to a single-step firing operation, was made into a reusable system with the capability of being loaded from a large reservoir of premixed foam, and was modeled toward facilitating easy handling by a diver. The external leak plugger has been extensively tested, both in the laboratory and in the field, and is now a viable system for forming rigid foam plugs in holes or ruptures in marine vessels.

Deployment of the external leak plugger has been measurably advanced by a system integration study which selected the optimum leak plugger shipping configuration, determined the most cost-effective production scenario, and led to the filing of a formal application for a DOT exemption for shipping the loaded device. EMSC also developed a training program, including a narrated film and a slide presentation.

In addition, a detailed analytical study of the development and use of a scaled-up leak-plugging system has produced a recommendation for the production of a larger version of the external leak plugger.

It is recommended that further research be conducted in the following areas:

1. Develop a scaled-up device for plugging holes up to 0.30 m (12 inches) in diameter
2. Improve operations for loading foam into leak-plugging devices to reduce the time for loading
3. Determine compatibility of the rigid foam plug with selected hazardous materials

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## APPENDIX A

## PREPROTOTYPE COST ANALYSIS

A cost analysis involving a comparison between a reusable system and a throwaway system begins with the procedures and manhours for fabrication and use of a reusable delivery system characterized by a useful life estimated at six cycles. These are listed in Table A-1 while Table A-2 tabulates the same for a throwaway delivery system of one cycle. Since applicator tips and foam ingredients are common to both systems, they are not included in the evaluation. The cost analysis concludes in Table A-3 by combining the per-cycle labor and material costs for both the reusable and the throwaway systems for comparison. Material costs are totaled from Table 1 and labor costs are calculated at a nominal rate of $25 per hour. Not surprisingly, the throwaway system tallies out costing 80% more than the reusable system on a per-cycle basis. However, if the useful life of the reusable delivery system can be extended beyond the conservative estimate of six cycles, and the probability is it can, then the per-cycle material costs for the reusable case will be reduced even further.

TABLE A-1. PROCEDURES FOR FABRICATION AND USE OF REUSABLE DELIVERY SYSTEM (EXCLUDING APPLICATOR TIP)
(Useful Life Estimated at Six Cycles*)

| STEP | ESTIMATED TIME (HRS) | |
|---|---|---|
| 1. SYSTEM (LANCE-PRESSURANT ASSEMBLY) FABRICATION | | |
| 1.1 Ordering | 0.5 | |
| 1.2 Machining | 0.5 | |
| 1.3 Welding | 1.5 | |
| 1.4 Assembly | 1.0 | |
| 1.5 Leak-checking (lance) | 0.5 | |
| 2. LANCE LOADING | | |
| 2.1 Foam Formulation | 0.5 | |
| 2.2 Foam Loading (filling port crimped & sealed) | 1.0 | |
| 2.3 Weighings | 0.5 | |
| 2.4 Buoyancy Package | 0.5 | |
| 2.5 Pressurant Assembly Attachment | 0.5 | |
| 3. SYSTEM SHIPPING | | |
| 3.1 Shipping Container Fabrication | 1.0 | |
| 3.2 Shipping Instructions | 0.5 | |
| 3.3 Transportation (surface, round-trip) | - | $50 |
| 3.4 On-site Storage & Handling | 0.5 | |
| 4. LANCE RELOADING | | |
| 4.1 Disassembly | 0.5 | |
| 4.2 Cleanout | 1.0 | |
| 4.3 Reassembly (new rupture discs/filling port mod.) | 1.0 | |
| 4.4 Leak-checking | 0.5 | |
| 4.5 Foam Loading (filling port crimped & sealed) | 1.0 | |
| 4.6 Weighings | 0.5 | |
| 4.7 Buoyancy Package & Pressurant Assembly Reattachment | 0.5 | |
| 5. SUBSEQUENT LANCE RELOADINGS (X4) | | |
| 5.1 Substeps 3.2, 3.3 & 3.4 | 1.0 | $50x4.5 |
| 5.2 Step 4. | 5.0 | |

* After six cycles, a minor overhaul of the system requiring replacement of the filling port tube and, perhaps, replacement of the $CO_2$ inflator O-ring would extend the useful life for another six cycles.

TABLE A-2. PROCEDURES FOR FABRICATION AND USE OF THROWAWAY DELIVERY SYSTEM (EXCLUDING APPLICATOR TIP) (Useful Life - One Cycle)

| STEP | ESTIMATED TIME (HRS) |
|---|---|
| 1. SYSTEM (LANCE-PRESSURANT ASSEMBLY) FABRICATION | |
| 1.1 Ordering | 0.5 |
| 1.2 Machining | 0.5 |
| 1.3 Welding | 1.5 |
| 1.4 Assembly | 1.0 |
| 1.5 Leak-checking (lance) | 0.5 |
| 2. LANCE LOADING | |
| 2.1 Foam Formulation | 0.5 |
| 2.2 Foam Loading (filling port crimped & sealed) | 1.0 |
| 2.3 Weighings | 0.5 |
| 2.4 Buoyancy Package | 0.5 |
| 2.5 Pressurant Assembly Attachment | 0.5 |
| 3. SYSTEM SHIPPING | |
| 3.1 Shipping Container Fabrication | 1.0 |
| 3.2 Shipping Instructions | 0.5 |
| 3.3 Transportation (surface, one-way) | - $25 |
| 3.4 On-site Storage & Handling | 0.5 |

TABLE A-3. DELIVERY SYSTEM COST ANALYSIS (EXCLUDING APPLICATOR TIP)≠

LABOR COSTS (HRS)

| PROCEDURE STEP | 1 | 2 | 3 | 4 | 5 | TOTAL | PER CYCLE |
|---|---|---|---|---|---|---|---|
| REUSABLE SYSTEM | 4.0 | 3.0 | 2.0 | 5.0 | 24.0 | 38.0 | 6.3 |
| THROWAWAY SYSTEM | 4.0 | 3.0 | 2.0 | - | - | 9.0 | 9.0 |

MATERIAL COSTS ($)

| | LANCE | PRESSURANT ASSEMBLY | TRANSPORTATION | TOTAL | PER CYCLE |
|---|---|---|---|---|---|
| REUSABLE SYSTEM | 238 | 17 | 275 | 530 | 88 |
| THROWAWAY SYSTEM | 183 | 15 | 25 | 223 | 223 |

COMBINED COSTS/CYCLE ($)

| | LABOR | MATERIAL | TOTAL |
|---|---|---|---|
| REUSABLE SYSTEM | 158 | 88 | 246* |
| THROWAWAY SYSTEM | 225 | 223 | 448 |

≠ Cost of foam ingredients not included.

* Personnel training in the use of the foam loading system and in reloading techniques is not included per se, but costs of such (estimated at 40 hrs) would be pro rated over all the lances and all reloadings, reducing this add-on to miniscule proportions.

APPENDIX B

EXTERNAL LEAK PLUGGER - DOT EXEMPTION APPLICATION

(1) This application for an exemption from the requirements of the DOT Hazardous Materials Regulations is being submitted to obtain administrative relief therefrom on the basis of levels of safety consistent with the public interest and the policy of the Hazardous Materials Transportation Act. The application is being submitted in triplicate to: Office of Hazardous Materials Regulation, U.S. Department of Transportation, Washington, D.C. 20590, Attention: Exemptions Branch.

(2) The exemption is sought from the following DOT regulations:

§ 173.301(h) Compressed gas containers. Compressed gases must be in metal containers built in accordance with the DOT specifications (as shown in an accompanying table) in effect at the time of manufacture, and marked as required by the specification and the regulation for retesting if applicable.

§ 173.304 Charging of cylinders with liquefied compressed gas. (a) Detailed charging requirements. Liquefied gases shall be charged in accordance with the specific provisions of subparagraph (2) of this paragraph or paragraph (e) of this section. Where charging requirements are not specifically prescribed, liquefied gases, except gas in solution or poisonous gas, must be shipped, subject to the applicable paragraphs under General Requirements for Shipment (see §173.301), the charging requirements of this section for liquefied compressed gas, or the charging requirements for mixtures (see §173.305), in containers manufactured under specifications, as follows:
(1) Specifications 3, 3A, 3AA, 3B, 3BN, 3D, 3E, 4, 4A, 4B, 4BA, 4B-ET, 4BW, 9, 25, 26, 38, 39, 40, or 41, except that no specification 9, 39, 40 or 41 packaging may be charged and shipped with a mixture containing a pyrophoric liquid, carbon bisulfide

(disulfide), ethyl chloride, ethylene oxide, nickel carbonyl, spirits of nitroglycerin, or poisonous material (Class A, B, or irritating material), unless specifically authorized in this part. (For flammable gases, the internal volume of a specification 39 cylinder must not exceed 75 cubic inches.)

(2) The following restrictions must be complied with for the gas named:

| Kind of gas | Maximum permitted filling density (percent) | Containers marked as shown in this column or of the same type with higher service pressure must be used |
|---|---|---|
| Methyl chloride | 84 | DOT-3A225, DOT-3AA225, DOT-3B225, DOT-4A225, DOT-4B225, DOT-4BA225, DOT-4BW225, DOT-3, DOT-4, DOT-25, DOT-26-300,DOT-38, DOT-3E1800, DOT-4B204ET. Cylinders complying with DOT-3A150, DOT-3B150, DOT-4A150, and DOT-4B150 manufactured prior to Dec. 7, 1936 are also authorized. |

§ 173.304(e) Refrigerant gases. Refrigerant gases which are nonpoisonous and nonflammable under this part, must be shipped in cylinders as prescribed in paragraph (a)(1) or (2) of this section, or as follows:

(1) Specifications 2P and 2Q. Inside metal containers packed in a strong wooden or fiberboard box of such design as to protect valves from injury or accidental functioning under conditions incident to transportation. Pressure in the container must not exceed 85 pounds per square inch absolute at 70°F. Each completed metal container filled for shipment must be heated until content reaches a minimum temperature of 130°F without evidence of leakage, distortion, or other defect. Each outside shipping container must be plainly marked "Inside Containers

Comply With Prescribed Specification."

§ 173.305 Charging of cylinders with a mixture of compressed gas and other material. (c) Nonpoisonous and nonflammable mixtures. Mixtures containing compressed gas or gases including insecticides, which mixtures are nonpoisonous and nonflammable under this part must be shipped in cylinders as prescribed in §173.304(a) or as follows:

(1) Spec. 2P. Inside metal containers equipped with safety relief devices of a type approved by the Bureau of Explosives and packed in strong wooden or fiber boxes of such design as to protect valves from injury or accidental functioning under conditions incident to transportation. Pressure in the container must not exceed 85 psi absolute at 70°F. Each completed metal container filled for shipment must be heated until content reaches a minimum temperature of 130°F., without evidence of leakage, distortion or other defect. Each outside shipping container must be plainly marked "INSIDE CONTAINERS COMPLY WITH PRESCRIBED SPECIFICATIONS."

§ 173.306 Limited quantities of compressed gases. (a) Limited quantities of compressed gases for which exceptions are permitted as noted by reference to this section in §172.101 of this subchapter are excepted from labeling (except when offered for transportation by air) and, unless required as a condition of the exception, specification packaging requirements of this subchapter when packed in accordance with the following paragraph.

(3) When in a metal container charged with a solution of materials and compressed gas or gases which is nonpoisonous, provided all of the following conditions are met.

(ii) Pressure in the container must not exceed 180 psig at 130°F. If the pressure exceeds 140 psig at 130°F but does not exceed 160 psig at 130°F, a specification DOT 2P inside metal container must be used; if the pressure exceeds 160 psig at 130°F, a specification DOT 2Q inside metal container

must be used. In any event, the metal container must be capable of withstanding without bursting a pressure of one and one-half times the equilibrium pressure of the content at 130°F.

(v) Each completed container filled for shipment must have been heated until the pressure in the container is equivalent to the equilibrium pressure of the content at 130°F (55°C) without evidence of leakage, distortion, or other defect.

(3) The following parties are listed as co-applicants:

(a) United States Coast Guard Research and Development Center
Avery Point
Groton, CT 06340
(Mr. Steven Rosenberg,
Mr. David Motherway,
Telephone: 203-445-8501)

(b) Rockwell International,
Environmental and Monitoring Services Center
2421 W. Hillcrest Drive
Newbury Park, CA 91320
(Mr. Robert Melvold,
Dr. Bart Tuffly,
Telephone: 805-498-6771)

(4) The applicants propose that a device for plugging underwater holes up to 0.2 meter (8 inches) in diameter, developed for the United States Coast Guard by Rockwell International and known as the external leak plugger, be exempted from the DOT regulations listed under (2) above.

A sketch of the prototype leak-plugging system appears in Figure B-1, wherein the basic assemblies and certain important features are

listed. The leak-plugging system comprises two major assemblies: the foam delivery system and the applicator tip assembly. The foam delivery system consists of a foam-containing lance and a gas pressurant assembly. The storage or containment system involves a metal tube with a burst disc assembly attached to each end. Within each burst disc assembly is a rupture disc,

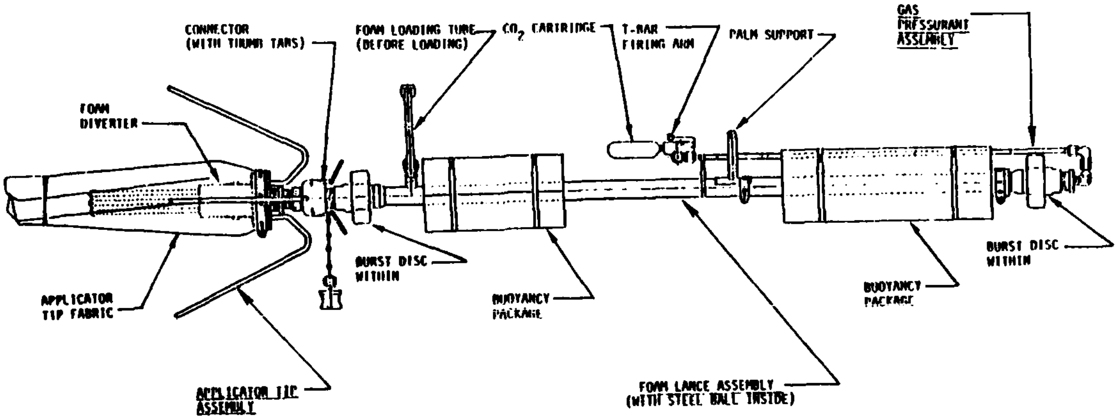



Figure B-1. Prototype External Leak Plugger

predesigned to break away at 300 psi, and a vacuum support disc. The driving force for the transfer or expulsion function is provided by carbon dioxide ($CO_2$) from an ordinary $CO_2$ gas cartridge located in the gas pressurant assembly, which also includes an inflator, a manifold stem flow restrictor, and a gas expansion tube. When firing the device, the firing mechanism punctures the gas cartridge, releasing $CO_2$ gas which feeds into the lance, breaking the rupture discs and expelling the fluid foam, a polystyrene mixture. (The polystyrene formulation is prepared in accordance with a Monsanto Research Corporation formula, Sun et al (1976), that involves dissolving a given quantity of solid polystyrene in methyl chloride, a liquefied compressed gas, followed by the addition of Freon 13B1, another compressed gas which serves as a pneumatogen. The foam formulation is loaded under pressure by means of a unique foam transfer system

connected to the lance through a filling port. When it is determined that the desired amount of foam has been loaded, the loading tube is crimped off and silver-brazed.)

Field operation of the device would usually involve attaching an applicator tip (there is only one size) to the front end of the lance by means of the Kamlok connector, and then screwing a $CO_2$ gas cartridge into the inflator in the gas pressurant assembly, thus arming the device. When the operator wishes to fire the system (after inserting the applicator tip into the hole to be sealed) he squeezes the T-bar/palm support firing mechanism puncturing the gas cartridge, thereby feeding carbon dioxide gas through the gas expansion tube into the rear of the lance. At this point the rear rupture disc breaks and the pressurant gas enters, driving a chrome steel ball against the pressurized foam mix, breaking the front rupture disc, and expelling the polystyrene foam from the lance. Having previously been dissolved in liquefied compressed gases, the polystyrene comes out of solution as the compressed gases vaporize at the lower ambient pressures. At this time a polystyrene matrix forms, expanding and solidifying, resulting in a rigid foam plug. The matrix consists of small bubbles of evaporated solvent having walls of thin membranes of solid polystyrene. In addition, when the steel ball strikes the front burst disc assembly, it forms a seal, preventing the pressurant gas from entering the foam plug. The entire operation is completed in only a few seconds.

For underwater applications, the external leak plugger is equipped with a buoyancy package, as seen in Figure B-1, so that the charged delivery system will be almost neutrally buoyant before use, and yet the spent lance will have a somewhat positive buoyancy. This enables the scuba diver to release the spent lance after detaching it from the foam plug, by means of a Kamlok connector, with the assurance that it will rise to the surface of the water where operational

personnel can retrieve it for reuse. In addition, the buoyancy package is split into two sections so that its center of buoyancy will coincide with its center of gravity, thereby making it easier for a scuba diver to manipulate.

A detailed assembly drawing EMSC No. 10000060 and detailed working drawings, EMSC Nos. 10000061 and 10000062 are included with the exemption application submitted. The proposed shipping configuration of the external leak plugger (best visualized by viewing the assembly drawing) consists of the foam lance assembly attached to the gas pressurant assembly with a $CO_2$ cartridge installed in the inflator. The $CO_2$ cartridge contains 0.6 oz. (16 gm) net wt. liquefied carbon dioxide, classed as a nonflammable gas, and complies with the applicable DOT air freight regulations as certified by the manufacturer, Sparklett Devices, St. Louis, MO. To prevent accidental $CO_2$ activation of the device during shipment, the inflator firing arm is firmly secured by a tubing clamp (Scientific Products, P/N C6095-2).

The applicator tip hardware and fabric assemblies will not be shipped attached to the modified foam-loaded delivery system. Instead, the 633F Kamlok coupler will be closed off by means of a 634A Kamlok plug, tied to the coupler by chain. The calculated working pressure for the 1" OD foam lance is 1600 psi at ambient temperature while the Kamlok coupler/plug combination is rated by the manufacturer for an operating pressure of 250 psi at 225 F. The ability of the plugged Kamlok coupler to contain the foam mix (in the event of a leak past the rupture disc) has been tested and found quite satisfactory. It should be noted, however, that throughout dozens of laboratory and field tests of the prototype external leak plugger a premature unintentional rupture of the burst discs has never occurred. In addition, a shelf-life test designed to provide information on the capability of the loaded foam lance to survive one-year storage periods without any weight loss has shown, after four months of storage, no loss in weight measured to $2.2 \times 10^{-4}$ lb ($1.0 \times 10^{-4}$ kg). The lance is

similar to prototype lances used in testing, and was loaded with 0.70 lb (0.317 kg) of polystyrene foam in the usual manner.

No previous exemptions, approvals or permits for the external leak plugger exist.

(5) The polystyrene foam used in the external leak plugger is produced as follows: A powdered or pellet form of solid polystyrene is dissolved in a liquefied gas, methyl chloride ($CH_3Cl$), while under relatively high pressure. When the pressure is released, at the point of use, the solvent instantly vaporizes, leaving behind the dissolved plastic which precipitates as thin, solid membranes surrounding the evaporated solvent. In other words, a matrix of small bubbles is formed having solid polystyrene walls and containing solvent vapor. A pneumatogen or blowing agent, bromotrifluoromethane ($CBrF_3$)(Freon 13B1), is added to increase foaming at low temperatures, because of its low boiling point of 215 K(-72 F). It also imparts nonburning characteristics to the gas mixture (Sun et al (1976)). Minor additions of other materials are made to the solution to aid in nucleation and lubrication. Glass microballoons serve as condensation nuclei for the formation of the small bubbles ultimately seen as the fine structure in the foam produced, and Igepal, a surface active agent, serves to enhance foaming and act as a lubricant so that the material flows through valves and tubing more easily. A more detailed description of the mechanism for the production of these foams can be obtained from Sun et al (1976).

The theoretical percentage composition of the mixture is as follows:

| Ingredient | Weight Percent |
|---|---|
| Polystyrene | 52.98 |
| Glass Microballoons | 1.00 |
| Igepal CO970 | 3.43 |
| Methyl Chloride ($CH_3Cl$) | 28.46 |
| Freon 13B1 ($CBrF_3$) | 14.13 |
| | 100.00 |

The solidified foam produced from the polystyrene foam mixture is white and has a slightly springy texture and is rather chemically inert. The density of the solidified foam varies from 1 $lbm/ft^3$ to above 2.4 $lbm/ft^3$, depending upon the conditions under which the foam solidification takes place.

Two forms of polystyrene polymer are available for use in the mixture. One is Lustrex HH100, a "granular crystal" form, and the other is Lustrex HH101, a pellet form containing a small amount of lubricant, both of which are produced by the Monsanto Corporation. The glass microballoons are a product of Emerson and Cumings Inc., while Igepal CO970 is a surfactant produced by GAF Corp. By DOT definition, methyl chloride ($CH_3Cl$) is a flammable compressed gas, whereas bromotrifluoromethane ($CBrF_3$) is a liquefied compressed gas. Physical properties of $CH_3Cl$, including its vapor pressure curve, reported by Braker et al (1971), and tabulated vapor pressure and liquid density values for $CBrF_3$ can be found in the attachment to this appendix. Also included in the attachment is the vapor pressure curve of a polystyrene foam mixture with a $CH_3Cl:CBrF_3$ mixture weight ratio of 4:1.

Although one of the mixture components, namely $CH_3Cl$, is defined as a flammable compressed gas, the mixture of gases employed is reported by Sun et al (1976) to be non-combustible in the flame of a propane torch. In the tests reported, an 80% by weight methyl chloride, 20% Freon 13B1 mixture was determined to be non-burning during the entire discharge of a supply cylinder. The $CH_3Cl:CBrF_3$ mixture ratio in the applicants' leak plugging foam mixture is 2:1 and, therefore, even richer in the nonflammable compressed gas component. It would be reasonable, therefore, to conclude that the $CH_3Cl/CBrF_3$ mixture with a weight ratio of 2:1 is a non-combustible gas mixture and subject to DOT regulations pertaining to a liquefied compressed gas.

(6) Polystyrene foam mixtures of the 4:1 $CH_3Cl:CBrF_3$ variety have been shipped by motor vehicle from the Monsanto Research Corporation in Dayton, OH. Authorization for the shipments were obtained through DOT special permit No. 6976 issued March 18, 1975 and DOT exemption No. E7093 issued in January of 1976. In the latter case, foam-loaded glass bottles were shipped inside metal containment vessels that were a little larger than the bottles and that had holes in them for passage of exuding foam (and vapor) in the case of bottle breakage. No accidents are known to have occurred.

(7) The following modes of transportation are proposed: cargo aircraft, cargo vessel, and motor vehicle on public highway. Since the foam mixture is proposed to be shipped in the modified external leak plugger, which is a completely closed, metal system capable of withstanding internal pressures much greater than the mixture vapor pressure, and since the modified leak plugger will be shipped in crates which conform to the DOT regulations, there are no identifiable increased risks.

(8) The proposed duration sought for the exemption is the maximum allowable, i.e., two years from date of issuance. During this period the Coast Guard and Rockwell International will be evaluating the device in use, that is, plugging holes in marine cargo vessels, as incidents occur. It is for this reason that the exemption is being sought: that the device may be shipped to Coast Guard Strike Team headquarters and from thence to sites of hazardous material spill incidents as required. Thus the device will be used to plug the ruptures and prevent further environmental pollution.

(9) As stated above, the device itself is designed to "protect against risks to life and property which are inherent in the transportation of hazardous material in commerce." This is the reason for its existence. The DOT regulations to which the exemption is primarily

directed, namely §173.301(h), §173.304(a), §173.304(e) and §173.305(c), basically refer to the types of DOT-rated containers which are approved for the two individual gases and/or mixture of the two gases used in the polystyrene foam mixture. The device in question had to be designed for a particular function and, thus, use of a DOT-rated cylinder was precluded for obvious technical reasons. Nevertheless, the device configuration proposed for shipping is comparable to the DOT-rated cylinders in the level of safety which it provides. Each device will be loaded with no more than 3/4 lb (350 gm) of foam mix and less than half of this mixture will be compressed gas. The foam tank itself has a volume of 27 cu. in. (440 cc).

Thus, the modified-for-shipping external leak plugger is a closed system capable of containing the foam mixture if either front or rear internal rupture discs were to break prematurely, which has never happened during the dozens of tests conducted with the device. In addition, even if the foam were able to escape from the confines of the leak plugger (and it should be noted that this is very unlikely), the foam would simply expand up to a limiting volume of approximately 390 cu. in. (3-1/2 liters). The result would be a quantity of solidified polystyrene foam, similar in texture to the white packing worms so commonly found in shipping crates.

The exemption being sought is also directed to another set of DOT regulations, namely §173.306(a)(3)(ii) and (v), dealing with limited quantities of compressed gases. Since in many respects, except the subparagraphs cited, the leak plugger qualifies for this shipment category, this information may, therefore, expedite the granting of an exemption. The device is a metal container charged with a solution of materials and compressed gas or gases which is nonpoisonous and its capacity does not exceed 50 cu. in., while the liquid content of the material and gas does not completely fill the container at 130$^{\circ}$F. The container will be packed in strong outside packagings

and the outside packaging will be marked as prescribed. Since subparagraph (ii) deals with certain maximum pressures allowable in the container at 130$^{O}$F and since experimental data of this nature does not exist for the mixture ratio of gases used in the polystyrene foam being employed, calculations of the mixture pressure have been made. Assuming ideal behavior, since both $CH_3Cl$ and $CBrF_3$ are hologenated compounds and, therefore, similar in certain chemical respects, the total gas mixture pressures at 70$^{O}$F and 130$^{O}$F are calculated as follows:

| | | |
|---|---|---|
| GIVEN: | $A$ | $= CH_3Cl$ |
| | $WT_A$ | $= 100$ gm |
| | $MW_A$ | $= 50.5$ |
| and | $B$ | $= CBrF_3$ |
| | $WT_B$ | $= 49$ gm |
| | $MW_B$ | $= 148.9$ |

and, from Raoult's law:

$$p_A = x_A \, p_A^o$$

$$p_B = x_B \, p_A^o$$

$$P = p_A + p_B$$

Therefore, <u>at 70$^{O}$F</u>:

with $p_A^o \approx 73$ psia (Attachment)

$p_B^o \approx 209$ psia (Attachment)

then $p_A = 0.857\ (73) = 62.6$ psia

$p_B = 0.143\ (209) = 29.9$ psia

and $P = 92.5$ psia

Also, <u>at 130$^{o}$F</u>:

$$\text{with } p_A^o \approx 180 \text{ psia (Attachment)}$$
$$p_B^o \simeq 457 \text{ psia (Attachment)}$$

$$\text{then } p_A = 0.857\ (180) = 154 \text{ psia}$$
$$p_B = 0.143\ (457) = 65 \text{ psia}$$

$$\text{and } P = 219 \text{ psia}$$

As a check on the assumption of ideal behavior, a calculation of the total gas mixture pressure for the 4:1 ratio $CH_3Cl$: $CBrF_3$ mixture was performed and compared with the experimental results obtained on such a mixture at 70$^{o}$F (by Monsanto Research Corp.) and shown as a curve in the attachment. The total gas mixture pressure was found to be 83.6 psia, a value which lies essentially on the experimentally-developed curve, thereby, providing an indication that the assumption of ideality may be accurate in the case of these mixtures.

Subparagraph (v) of §173.306(a)(3) requires heating the completed container filled for shipment until the equilibrium pressure of the contents at 130$^{o}$F is reached. Since the internal rupture discs are programmed to break at 300 psi, it would be in the best interests of the device to have the shipment of the device exempted from this regulation, as well, and, thereby, not take the risk of jeopardizing the designed performance of the leak plugger by stressing it unnecessarily.

(10) The applicants so seek to have the application processed on a priority basis since there is a vital and immediate need for systems that can prevent dispersion of hazardous chemicals into the environment. It is far better and easier to prevent a hazardous chemical from entering a waterway than it is to attempt to remove it after entry. An

effort has been and is being conducted at the Environmental Monitoring & Services Center of Rockwell International in which dramatic improvements have been and are being made to an existing leak-plugging system designed for plugging underwater holes in ruptured marine cargo vessels. The effort is sponsored by the U.S. Coast Guard Research & Development Center, Groton, CT under Contract No. DOT-CG-81-78-1817. It is imperative that the work continues in an expeditious manner, which requires testing the device under actual spill conditions. This, in turn, necessitates shipping the loaded devices to the Coast Guard Strike Team headquarters for storage, until needed, and subsequently deploying them to the scene of a spill incident for use. In order that valuable time is not lost while this application awaits processing in the usual manner, the applicants urge that their request for consideration of the application on a priority basis be granted.

(11) The applicants are residents of the United States.

## REFERENCES


1. Braker, W., and A. Mossman (1971), Methyl Chloride. In Matheson Gas Data Book, 5th Edition, East Rutherford, N.J., pp 369-374.

2. Sun, S. M., J. L. Schwendeman and I. O. Salyer (1976), Feasibility of Use of Plastic Foams for Small Vessel Flotation Devices, Report AD-A021-076/5SL (MRC-DA-518), Monsanto Research Corporation for U.S. Coast Guard, Department of Transportation, Washington, D.C., Contract No. DOT-CG-52454-A.

ATTACHMENT

SELECTED FOAM COMPONENT PROPERTIES

TABLE B-1

METHYL CHLORIDE PHYSICAL CONSTANTS (Braker et al [1971])

| | |
|---|---|
| Molecular Weight | 50.49 |
| Vapor Pressure @ 70°F. | 58.7 p.s.i.g. (4.1 kg./cm.$^2$ gauge) |
| Specific Volume @ 70°F., 1 atm. | 7.6 cu. ft./lb. (474.4 ml./g.) |
| Boiling Point @ 1 atm. | −11.6°F. (−24.22°C.) |
| Freezing Point @ 1 atm. | −143.5°F. (−97.5°C.) |
| Specific Gravity, Gas @ 0°C., 1 atm. (Air = 1) | 1.74 |
| Density, Gas @ 0°C., 1 atm. | 2.3075 g./l. |
| Density, Liquid @ −24°C. | 0.997 g./ml. |
| Critical Temperature | 289.6°F. (143.1°C) |
| Critical Pressure | 968.7 p.s.i.a. (65.9 atm.) (68.1 kg./cm.$^2$ absolute) |
| Critical Density | 0.363 g./ml. |
| Specific Heat, Liquid @ 20°C. | 0.381 cal./(g.) (°C.) |
| Specific Heat, Gas @ 25°C., 1 atm., *Cp* | 0.1926 cal./(g.) (°C.) |
| *Cv* | 0.150 cal./(g.) (°C.) |
| Specific Heat Ratio, Gas @ 25°C., 1 atm., *Cp/Cv* | 1.284 |
| *Latent Heat of Vaporization @ b.p.* | 101.3 cal./g. |
| Latent Heat of Fusion @ m.p. | 31 cal./g. |
| Thermal Conductivity, Liquid @ 20°C. | 0.093 BTU/(hr.) (ft.$^2$) (°F./ft.) [$0.0_3384$ cal./(sec.) (cm.$^2$) (°C./cm.)] |
| Gas @ 0°C. | 0.00537 BTU/(hr.) (ft.$^2$) (°F./ft.) [$0.0_4222$ cal./(sec.) (cm.$^2$) (°C./cm.)] |
| Heat of Formation, Gas @ 25°C. | −20.66 kcal./mole (−409.1 cal./g.) |
| Flammable Limits in Air | 8.1-17.2% (by volume) |
| Autoignition Temperature | 1170°F. (632°C.) |
| Viscosity, Liquid @ 20°C. | 0.244 centipoise |
| Gas @ 20°C., 1 atm. | 0.0106 centipoise |
| Surface Tension @ 0°C. | 19.5 dynes/cm. |
| Solubility in Water @ 1 atm., @ 0°C. | 340 cc./100 cc. of water |
| @ 20°C. | 220 cc./100 cc. of water |

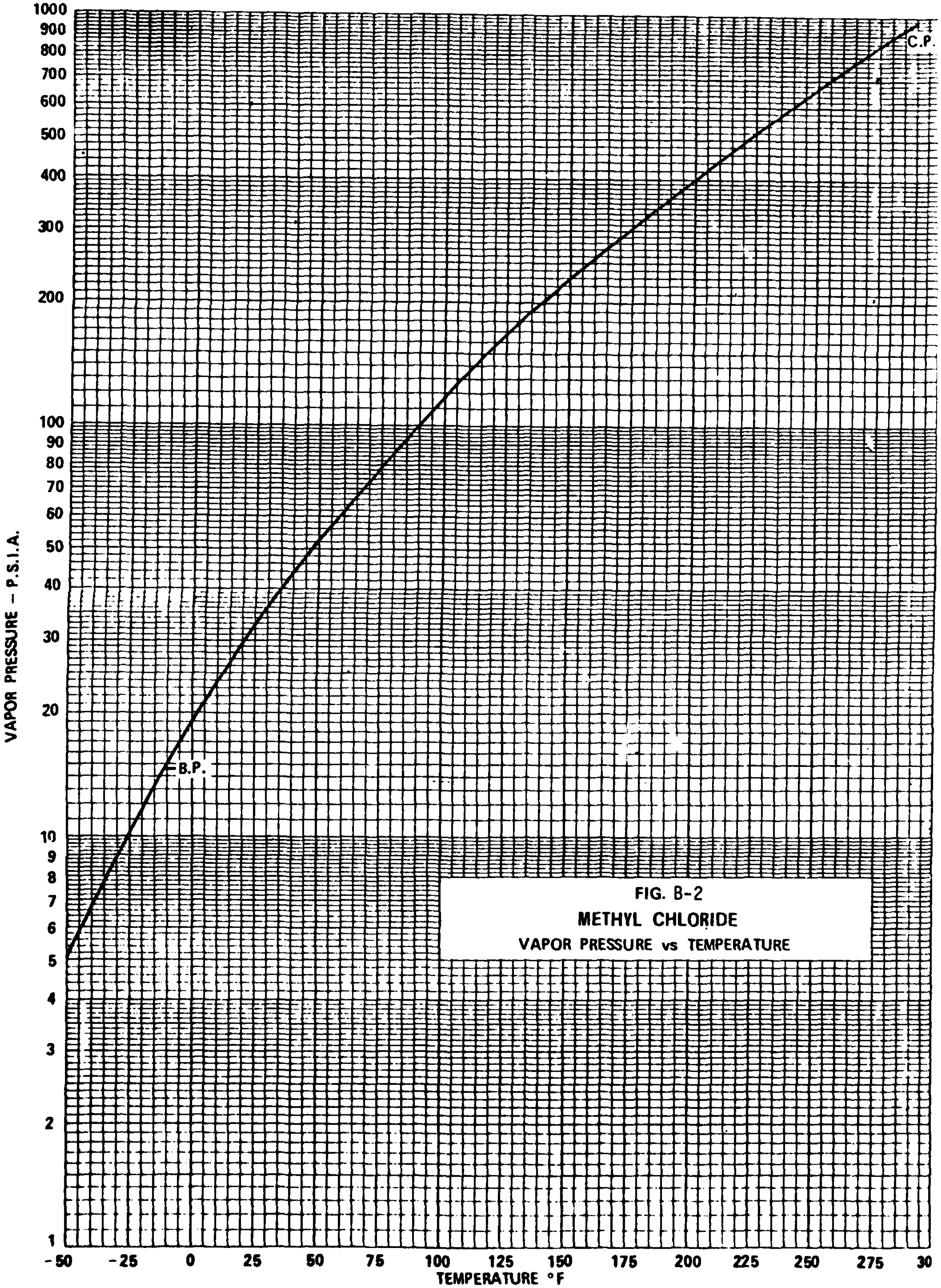



FIG. B-2
METHYL CHLORIDE
VAPOR PRESSURE vs TEMPERATURE

TABLE B-2

VAPOR PRESSURE AND DENSITY
OF SATURATED $CBrF_3$ (FREON 13B1)

| Temp °F | Pressure (psia) | $lb/ft^3$ (Liquid) |
|---|---|---|
| 29 | 100.8 | 108.71 |
| 40 | 138.6 | 104.65 |
| 60 | 186.0 | 100.20 |
| 80 | 244.4 | 95.22 |
| 100 | 315.2 | 89.42 |
| 150 | 559.2 | 60.71 |

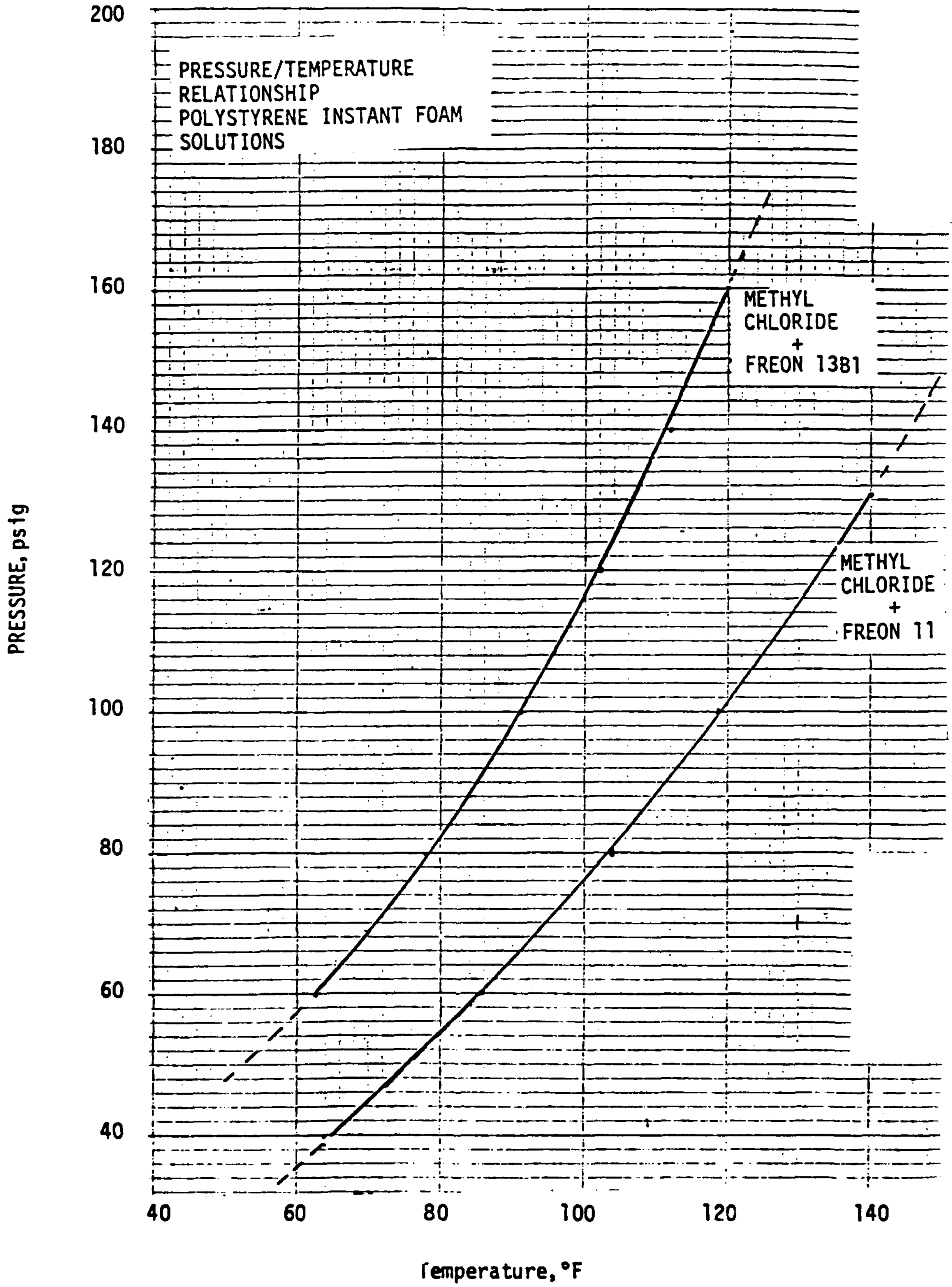



Figure B-3. Pressure as a Function of Temperature above Typical Single Component Foam Solutions. (Data Courtesy Monsanto Research Corporation)

## APPENDIX C

## FILM NARRATION

| NARRATION | FILM |
|---|---|
| The quantity of hazardous chemicals transported over navigable waters by tanker, parcel carrier, or barge, as well as the number of shipments, has increased with time, as would be expected in a growing, modern industrialized society. The increased traffic and handling has inevitably resulted in an increase in the number of pollution spill incidents. | 1. Stock footage of ocean, river, or harbor shipping |
| Department of Transportation background investigations have established hull penetration as a major volume source of hazardous chemical spills. Accordingly, the Coast Guard Research and Development Center has funded several programs to develop external patching and plugging techniques for damaged marine transport containers. | 2. Sequence of scenes showing spill situations, preferably of a type that can be handled by a leak plugger. |
| Rockwell International, through its Environmental Monitoring and Services Center, has been awarded research contracts in this area and, as a result, has successfully developed a hand-held external leak plugger. | 3. Exterior EMSC |
| This prototype leak-plugging system consists of three basic assemblies: the gas pressurant assembly, the foam lance, and the applicator tip. | 4. Leak plugger |
| The tip internal structure is comprised of a hardware unit made up of two aluminum discs, one larger than the other, joined by three aluminum rods. To the larger disc is attached a section of PVC pipe. This serves as a foam diverter to direct the incoming foam toward the forward end of the applicator tip. | 5. Applicator tip being assembled, picture and narration synchronized |
| A hose clamp is used to attach the tailored vinyl upholstery fabric to the hardware unit. The fabric bag is coated on the seams for waterproofing purposes. | |
| The foam lance consists of two burst diaphragm assemblies welded one to each end of a 3-foot length of 1-inch stainless-steel tubing. A vacuum support disc and a rupture disc are placed within each burst disc assembly. When assembled and loaded, the lance will contain a polystyrene foam formulation. A Kamlok connector is used to attach the foam lance to the applicator tip assembly. | 6. Foam lance assembly, parts demonstrated in sync with narration |

| NARRATION | FILM |
|---|---|
| The gas pressurant assembly attaches to the foam lance. Pressurant is supplied by a $CO_2$ gas cartridge which is inserted into an inflator unit. | 7. Gas pressurant assembly, demonstrated in sync with narration |
| The inflator unit has been adapted so that the firing pin which punctures the $CO_2$ gas cartridge has a T-bar handle attached to it. This provides the operator with a sturdy grip to assure better firing reliability. In addition, a palm support is provided for the operator's hand so that he can maneuver and fire the device with only one free arm, a capability that is often required in the field. | |
| The remainder of the gas pressurant assembly is a $CO_2$ expansion tube and a set of fittings by which the assembly is attached to the foam lance. | |
| At the Rockwell facility, technical personnel have developed procedures for loading the leak-plugging device. With the applicator tip not attached, the device is checked for leak-tightness using a gas leak detector. | 8. Helium leak check of foam lance assembly |
| The lance is then connected to the foam loading system using a loading port constructed of stainless-steel tubing. | 9. Lance attached to loading system |
| The loading engineer evacuates the lance and adds methyl chloride, a compressed gas, before loading the liquefied foam. The foam is a special Monsanto Corporation formulation developed under contract to the United States Coast Guard. It is prepared at the Rockwell facility by dissolving polystyrene pellets in methyl chloride and then adding Freon 13B1. | 10. Methyl chloride being added to lance |
| The engineer then transfers a measured quantity of premixed foam into the lance. | 11. Foam loading |
| When the loading operation is completed, the filling port is crimped off and the foam lance is removed from the loading system. A small amount of foam in the interconnecting passage is then expelled. | 12. Crimping loading port<br>13. Excess foam expelled |
| The end of the filling port is silver-brazed to assure a leaktight system, good for a one-year shelf life. | 14. Brazing crimped port |
| A split buoyancy package is attached to the device to provide suitable underwater buoyancy for maneuverability and to allow for recovery of the lance following use. | 15. Adding buoyancy packages |

| NARRATION | FILM |
|---|---|
| When the operator wishes to arm the device, he removes the connector safety plug and attaches the applicator tip. | 16. Removing plug and adding $CO_2$ cartridge |
| He then attaches a $CO_2$ gas cartridge, which arms the device. | |
| As seen in this laboratory test firing, the applicator tip is directed into a demonstration target hole. | 17. Lab test firing, positioning applicator tip in hole |
| By tripping the T-bar firing arm, the operator initiates the foam expulsion. | 18. Tripping firing arm |
| The applicator tip expands with the incoming foam. In less than 5 seconds, expulsion of the foam is complete. At the same time, the foam out-gasses, producing a solidified foam plug in the demonstration target hole. The entire operation, from firing to formation of a foam plug sufficiently rigid to seal the hole, is accomplished in less than 20 seconds. | 19. Applicator tip expanding |
| The lance is then disconnected from the applicator tip and allowed to float to the water surface, where it can be retrieved for future use. | 20. Removing lance from tip |
| In addition to many laboratory test firings, the leak plugger has also been demonstrated in field trials. To do this, a target was lowered into a swimming pool and maneuvered into the deepest portion by a team of certified divers. The target consisted of a 4-foot by 6-foot section of 1/2-inch plywood out of which a number of irregularly shaped holes had been cut. These holes ranged in size from a 2-1/2-inch circle to an 8-inch circle, and included triangular, rectangular, and square-shaped cuts. The plywood was attached to a Unitstrut assembly and then painted with black enamel to retard water damage. | 21. Placement of target in swimming pool |
| Once in place, the target was weighted to compensate for the increase in buoyancy which would result from inflated foam plugs. Almost a hundred pounds of additional weight was attached underwater by the divers. | 22. Adding weights to target base |
| After attaching the applicator tip and the $CO_2$ cartridge to the lance, thereby arming the leak plugger, the diver entered the water. | 23. Diver on deck<br>24. Diver entering water |

| NARRATION | FILM |
|---|---|
| He then swam to the target, inspected the area, and began his approach. | 25. Diver approach to target |
| While swimming and without using any portion of the pool for support, the diver aimed the lance at the target and introduced the applicator tip into the hole. In this case, the hole was a 4-inch, irregularly shaped circle. | |
| He tripped the firing mechanism, puncturing the $CO_2$ cartridge and expelling the polystyrene foam from the lance into the applicator tip. The surge of gas emanating from the applicator tip indicated the expulsion of foam from the lance. | 26. Tip expansion |
| With the introduction of foam, which takes less than 5 seconds, the applicator tip expanded to accommodate the solidifying foam, thereby plugging the hole. | |
| After waiting a few seconds, the diver detached the lance from the expanded foam plug by flipping the connector thumb-tabs and pulling the lance assembly free. The lance assembly then floated to the surface, easily available for recovery. | 27. Detaching lance<br>28. Recovering lance |
| In a second test, the diver approached the target to plug a 5-inch, irregularly shaped circle. He again, while swimming straight ahead, introduced the applicator into the target hole. | 29. Approaching target |
| The spacing rods are designed and positioned to assure proper plug formation, with the larger of two spheres on the side of the target opposite the diver. This puts the larger sphere inside the tank hull structure, in the case of an actual spill incident, preventing the foam plug from dislodging. | 30. Placement of tip, featuring alignment rods |
| When satisfied that the applicator tip was in position, he tripped the firing mechanism. A surge of gas vented from the tip as the foam entered. At the same time, the applicator tip fabric expanded with foam, filling the target hole. | 31. Tip expansion |
| As he had in the first test, the diver released the lance assembly after a few seconds, allowing it to float freely to the surface. | 32. Release of lance |

| NARRATION | | FILM |
|---|---|---|
| Gas bubbles of methyl chloride and Freon continue venting from the seams of the applicator fabric for some time after plug formation. | 33. | Completed plugs with gas bubble leakage |
| The device has been used successfully to plug simulated damage in the form of circular holes up to 8 inches in diameter and rectangular holes up to 4 inches by 8 inches. | 34. | Third approach to target |
| Without extensive training in the use of the leak plugger, United States Coast Guard Strike Team divers have used the device to successfully plug target holes such as these, even under conditions simulating extremely low visibility. | 35. | Different angle approach |
| After field trials similar to the ones shown in this film, the divers reported their satisfaction with the leak plugger. | 36. | Repeat of earlier tip expansion |
| Upon completion of this effort, the Coast Guard will have the added capability for reducing effects of hazardous chemical spills from ruptured marine cargo vessels. | 37. | Completed tips expanded in target |

APPENDIX D

SLIDE NARRATION

| NARRATION | SLIDES |
| --- | --- |
| There is a vital need for systems that can prevent dispersion of hazardous chemicals into the environment. The external leak plugger addresses that need. The purpose of this slide presentation is to provide the listener with the basic knowledge for deploying and using the external leak plugger. To do this effectively, the listener will be provided with the rationale for the external leak plugger, details pertaining to the construction and operation of the device, and a brief description of the testing it has undergone. Near the end of this narration, the ten basic steps for the proper operation of the external leak plugger will be reviewed. | 1. Spill incident |
| It is far better and easier to prevent a hazardous chemical from entering a waterway than it is to attempt to remove it after entry. | 2. Spill cleanup |
| As a result, the Coast Guard, as part of its Hazardous Material Amelioration Program, has developed a system for plugging holes and leaks in marine vessels carrying hazardous materials including oil. | 3. Cargo vessel |
| Research conducted by Rockwell International at its Environmental Monitoring & Services Center | 4. EMSC |
| and sponsored by the Coast Guard Research & Development Center demonstrated the feasibility of using a single-component polystyrene foam for this purpose. | 5. CG R&D Center |
| The polystyrene foam uses polystyrene granules such as seen here, and is prepared in accordance with a Monsanto Research Corporation formula | 6. Polystyrene granules |
| that involves dissolving a given quantity of the solid polystyrene in methyl chloride, a liquefied compressed gas, followed by the addition of Freon 13B1, another compressed gas which serves as a pneumatogen or blowing agent. | 7. Foam formula (sketch) |

| NARRATION | SLIDES |
| --- | --- |
| The function of the external leak plugger, shown here, is to contain and expel this foam upon demand within the design requirements calling for a portable, self-contained device operable by one man under water to depths of 50 feet and water temperatures as low as 29 degrees Fahrenheit. | 8. Actual leak plugger prototype |
| A sketch of the prototype leak-plugging system shows the basic assemblies and certain important features. The leak-plugging system comprises two major assemblies: the applicator tip assembly and the foam delivery system. | 9. Leak plugger sketch #1 |
| The foam delivery system consists of a foam-containing lance and a gas pressurant assembly. | 10. Leak plugger sketch #2 |
| The storage or containment lance involves basically a metal tube with a burst disc assembly attached to each end. | 11. Bare lance |
| Within each burst disc assembly is a rupture disc, predesigned to break away at 300 psi, and a vacuum support disc. | 12. Exposed burst disc assembly |
| A unique foam transfer system is used to load the foam formulation under pressure | 13. Foam transfer system |
| into the lance through a special loading tube. When it is determined that the desired amount of foam has been loaded, | 14. Special loading tube |
| the loading tube is crimped off and silver-brazed. | 15. Silver brazed tube |
| The driving force for the foam transfer or expulsion is provided by carbon dioxide from an ordinary $CO_2$ gas cartridge located in the gas pressurant assembly, which also includes an inflator, a manifold stem flow restrictor, and a gas expansion tube. | 16. Leak plugger sketch #3 |
| When firing the device, the firing mechanism punctures the gas cartridge, releasing $CO_2$ gas which feeds through the gas expansion tube into the lance, breaking the rupture discs and expelling the fluidized polystyrene foam mixture. | 17. Leak plugger sketch #4 |

| NARRATION | SLIDES |
|---|---|
| The applicator tip assembly provides the means by which the foam can be contained for the purpose of plugging ruptures or holes. It consists of a hardware assembly and an outer tailored fabric. | 18. Leak plugger sketch #5 |
| The hardware assembly provides the required connection, by Kamlok adaptor, to the foam delivery system, directs the incoming fluid in a specific pattern, and provides the internal structural support for the outer fabric. | 19. Applicator tip hardware assembly (Kamlok) |
| The hardware assembly consists of two discs, one larger than the other, attached together by three metal rods. | 20. Applicator tip hardware assembly (discs) |
| Connected to the larger disc is a foam diverter, which directs the incoming foam to the front of the applicator tip where the smaller disc directs the foam in a radial pattern. | 21. Applicator tip hardware assembly (diverter) |
| Also connected to the larger disc, but external to the resulting foam plug, are three spacing rods, located 120 degrees apart on an imaginary circle. | 22. Applicator tip hardware assembly (rods) |
| The hardware is covered with a vinyl upholstery fabric tailored to specific dimensions and, because of its flexibility and the need to reduce the cross-sectional area, the fabric is folded into pleats, as shown here, after applicator tip assembly. In addition, the fabric outer surface is coated with a polymeric material to provide a fabric surface compatible with most hazardous chemical cargos. | 23. Actual applicator tip |
| Upon introduction of fluid, it begins expanding to its originally tailored dimensions as the foam solidifies by outgassing, ultimately forming a rigid foam plug as seen here. Tests have shown that the polystyrene foam can form a well-shaped, rigid plug at the temperatures and pressures of interest, given the proper fabric construction. | 24. Foam plug |
| In this regard, the fabric is constructed with two lengthwise slots for venting the expelling gases. The pointer directs your attention to one of the exit vents, the other is on the opposite side of the foam plug. Suitable rigid foam plug formation dictates that the applicator tip be provided with adequate means for venting the solvent and blowing agent vapors present in the polystyrene foam mixture. | 25. Foam plug (1st vent exit) |

| NARRATION | SLIDES |
|---|---|
| In this slide the rigid foam plug is shown stripped of its outer fabric covering. The polystyrene, having previously been dissolved in liquefied compressed gases, comes out of solution as the compressed gases vaporize at the lower ambient pressures. | 26. Foam plug (stripped) |
| A closeup view shows the polystyrene matrix, consisting of small bubbles of evaporated solvent having walls of thin membranes of solid polystyrene. | 27. Foam plug cross-section |
| It should be noted that all aspects of satisfactory plug formation have been thoroughly investigated, resulting in dramatic improvements in the applicator tip design and performance. A sampling of various applicator tip fabrics tested is shown here. | 28. Various applicator tip fabrics |
| In earlier prototypes, it was necessary to vary the quantity of foam chemicals as a function of hole size, ambient pressure and temperature to avoid rupturing the fabric. | 29 . Ruptured foam plug |
| With the new applicator tip design, the relative importance of these effects is diminished because the tip's outer fabric assembly is strong enough to contain the large amount of polystyrene foam required for the maximum hole size to be plugged. | 30 . Laboratory foam plug #1 |
| This is due in a large part to the vent slot arrangement described earlier, whereby the volatilizing gases can be satisfactorily expelled. | 31 . Laboratory foam plug #2 |
| Consequently, the delivery system is now designed to deliver enough chemicals to provide sufficient expansion under the worst conditions of low temperature, high pressure, and maximum hole size, while at higher temperatures, lower pressures, and smaller hole sizes, excessive tip expansion is prevented through the containment provided by the new tip design. | 32 . Laboratory foam plug #3 |
| Many tests have been conducted with the system and they have included underwater laboratory tests at ambient and low temperatures, as well as | 33. Laboratory trough test |
| underwater field tests by Coast Guard Strike Team divers, who have used the device to successfully plug holes up to 8 inches in diameter. | 34. Diver underwater |

| NARRATION | SLIDES |
|---|---|
| For underwater applications, the external leak plugger is equipped with a buoyancy package so that the charged delivery system will be almost neutrally buoyant before use, and yet the spent lance will have a somewhat positive buoyancy. | 35. Leak plugger sketch #6 |
| This enables the scuba diver to release the spent lance after detaching it from the foam plug, by means of the Kamlok connector, with the assurance that it will rise to the surface of the water where operational personnel can retrieve it for reuse. | 36. Diver detaching lance |
| In addition, the buoyancy package is split into two sections so that its center of buoyancy will coincide with its center of gravity, thereby making it easier for a scuba diver to manipulate underwater. | 37. Floating spent lance |
| The spacing rods are designed and positioned to assure the proper plug formation with the larger of the two spheres on the side of the target opposite the diver, as seen in this slide showing an earlier version of the fabric design. This would, of course, put the larger sphere inside the tank hull structure, in the case of an actual spill incident, and would prevent the foam plug from dislodging. | 38. Single foam plug in target underwater |
| Field operation of the device would involve attaching an applicator tip (there is only one size) to the front end of the lance by means of the Kamlok connector, and then removing the safety clamp that secures the T-bar firing arm and prevents premature firing, thus arming the device. | 39. Leak plugger sketch #7 |
| When the operator wishes to fire the system (after inserting the applicator tip into the hole to be sealed) he squeezes the T-bar/palm support firing mechanism puncturing the gas cartridge, thereby feeding carbon dioxide gas through the gas expansion tube into the rear of the lance. | 40. Leak plugger sketch #8 |
| At this point the rear rupture disc breaks and the pressurant gas enters, driving a chrome steel ball within the lance against the pressurized foam mix, breaking the front rupture disc, and expelling the polystyrene foam from the lance. | 41. Leak plugger sketch #9 |

| NARRATION | SLIDES |
|---|---|
| It should be noted that the entire leak-plugging operation is completed in a matter of seconds. | 42. Diver with plug in target |
| As mentioned earlier, several prototypes of the external leak plugger have been fabricated and extensively tested, both in the laboratory and in the field, the latter by Coast Guard Strike Team divers who have reported satisfaction with the system. | 43. Several actual leak pluggers |
| An important aspect of the field testing was the vital feedback from the divers regarding the operator/device interface. Many helpful suggestions for modifications to the device were received and incorporated into the prototype design. | 44. Group at poolside |
| Thus, the firing procedure for the $CO_2$ gas cartridge was converted from the pulling of a lanyard, shown here, | 45. $CO_2$ cartridge/lanyard |
| to the squeezing of a T-bar/palm support, adding mechanical stability to the firing mechanism and increasing the reliability of the firing operation. | 46. T-bar/palm support |
| The foam buoyancy package, originally a single unit, was split into two sections, | 47. Leak plugger with single buoyancy package |
| as mentioned earlier, so that the center of buoyancy would coincide with the center of gravity, providing greater system maneuverability. | 48. Leak plugger with split buoyancy package |
| A motorized flattop barge was used in the most recent field tests of the prototype external leak plugger. | 49. Motorized flattop barge |
| These tests were conducted by the Coast Guard in Fishers Island Sound off the Connecticut coast from Avery Point. | 50. Group aboard barge |
| In this ocean environment, foam pluggings were made at circular hole sizes of 2, 4, 6, and 8 inches, while target depths varied from 2 to 12 feet. | 51. Field plugs in target (side view) |
| Expulsion efficiencies average 90 percent, while the time for expulsion in every case was on the order of a few seconds. | 52. Field plugs in target (front view) |

| NARRATION | SLIDES |
| --- | --- |
| The external leak plugger was designed to provide the Coast Guard Strike Team with a plugging device that would be easy to use and reliable. Numerous tests during the course of the research and development program have confirmed that this was achieved. In this regard, several design features are worthy of note: | 53. Leak plugger prototype |
| First, the device is easily portable and practical for one-man field operation with no requirement for external power, motors, or batteries. | 54. George holding leak plugger |
| Second, the system provides rapid response (within moments of activation, a foam plug is formed). | 55. Two foam plugs in target underwater |
| Third, the device provides a sturdy, rigid plug with complete or nearly complete plugging. | 56. Laboratory foam plug |
| Fourth, the device has considerable flexibility in its application to hole size, shape, and location. Successful plugging tests have been made with irregularly-shaped holes from 2-1/2 inches to 8 inches in diameter. | 57. Foam plug in target (rear view) |
| Fifth, the prototype has been proved in laboratory operations at temperatures as low as 32 degrees Fahrenheit, with one-hour immersion times, | 58. Laboratory trough test |
| and in field operations at temperatures ranging from 65 to 82 degrees Fahrenheit. | 59. CG officials viewing foam plug |
| Sixth, the system is sufficiently safe and easy to use for operation by personnel without extensive training. | 60. Diver(s) with leak plugger |
| Before closing the presentation, let us review the ten basic steps to follow in using the external leak plugger: | 61. External Leak Plugger Operation (ELPO) |
| 1. Remove the foam delivery system and applicator tip assembly from storage. | 62. ELPO Step 1 |
| 2. Detach the end plug from the Kamlok coupler by, first, flipping open one thumb tab and waiting. Use care! If a leak has occurred, foam could be present and this would be signalled by frothing emanating from the Kamlok coupler. If such is the case, close thumb tab and put device aside without using. If go-ahead is indicated, flip open the other thumb tab and remove Kamlok plug. | 63. ELPO Step 2 |

| NARRATION | SLIDES |
|---|---|
| 3. Attach applicator tip to Kamlok coupler. Adjust spacing rods so they are firmly in place, roughly 120 degrees apart. | 64. ELPO Step 3 |
| 4. Make certain $CO_2$ gas cartridge is screwed firmly into inflator firing mechanism. | 65. ELPO Step 4 |
| 5. Remove safety clamp from inflator firing mechanism. (Note: Device is now armed.) | 66. ELPO Step 5 |
| 6. Enter the water with the external leak plugger, approach target and, if the current and surge factors allow, introduce applicator tip into hole until spacing rods meet resistance. | 67. ELPO Step 6 |
| 7. Grasp the T-bar/palm support firing mechanism in one hand and squeeze. The foam plug will expand in 2 to 5 seconds. (Note: The operator can hear, feel, and see the effects of the foam expulsion.) During the first few seconds of plug formation, keep lance as immobile as possible. If surge is a factor, release lance for a moment. | 68. ELPO Step 7 |
| 8. Wait about 15 seconds after firing, then detach the lance from the foam plug by pushing the Kamlok coupler thumb tabs forward and pulling lance free with a twisting motion. | 69. ELPO Step 8 |
| 9. Release expended lance and lance will float to the surface for retrieval. | 70. ELPO Step 9 |
| 10. Carefully and safely inspect plugging results. | 71. ELPO Step 10 |
| This concludes our presentation. If there are any questions, your presenter will be happy to answer them at this time. | 72. Leak plugger prototype |

# APPENDIX E

# TRAINING PROGRAM HANDOUTS

EXTERNAL LEAK PLUGGER TRAINING PROGRAM

Lesson: The External Leak Plugger and How to Use it

Type: Film, Narrated Slides, Q&A Session

Time: One hour

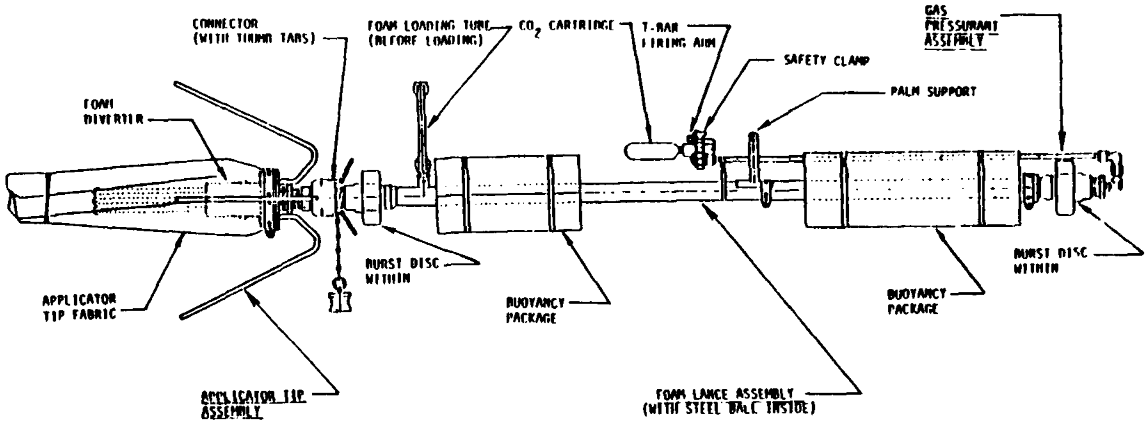
Objectives:

1. Provide brief background and basic concept
2. Describe the leak plugger in detail
3. Explain the operation of the leak plugger
4. Describe the research testing in general
5. Point out important improvements in the leak plugger
6. Provide a list of operational instructions
7. Discuss the device with the trainees – question and answer forum
8. Provide trainees with the opportunity to handle an inert leak plugger

Instructional Aids:

1. Film
2. Slides and tape cassette
3. Handouts:
   a. Training program format
   b. Sketch of the device
   c. Instruction sheet
4. External leak plugger (inert)

## EXTERNAL LEAK PLUGGER OPERATIONAL INSTRUCTIONS




External Leak Plugger

| STEP | OPERATION |
|---|---|
| 1 | Remove the foam delivery system and applicator tip assembly from storage. |
| 2 | Detach the end plug from the Kamlok coupler by, first, flipping open one thumb tab and waiting. Use care! If a leak has occurred, foam could be present and this would be signalled by frothing emanating from the Kamlok coupler. If such is the case, close thumb tab and put device aside without using. If go-ahead is indicated, flip open the other thumb tab and remove Kamlok plug. |
| 3 | Attach applicator tip to Kamlok coupler. Adjust spacing rods so they are firmly in place, roughly 120 degrees apart. |
| 4 | Make certain $CO_2$ gas cartridge is screwed firmly into inflator firing mechanism. |
| 5 | Remove safety clamp from inflator firing mechanism. (Note: Device is now armed.) |
| 6 | Enter the water with the external leak plugger, approach target and, if the current and surge factors allow, introduce applicator tip into hole until spacing rods meet resistance. |
| 7 | Grasp the T-bar/palm support firing mechanism in one hand and squeeze. The foam plug will expand in 2 to 5 seconds. (Note: The operator can hear, feel, and see the effects of the foam expulsion.) During the first few seconds of plug formation, keep lance as immobile as possible. If surge is a factor, release lance for a moment. |
| 8 | Wait for about 15 seconds after firing, then detach the lance from the foam plug by pushing the Kamlok coupler thumb tabs forward and pulling lance free with a twisting motion. |
| 9 | Release expended lance and lance will float to the surface for retrieval. |
| 10 | Carefully and safely inspect plugging results. |

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